Design and Development of a Low-cost Acoustic Device to Detect Pest Infestation in Stored Maize

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In

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Abstract

Insect damage in stored maize is one of the major post-harvest losses occurring in developing countries, especially in sub-Saharan Africa. To reduce economic losses, separation of infested grains from clean ones is critical and requires detection of infestation in stored grains. This study aimed at developing a rapid non-destructive detection system with three goals; - the first goal was to investigate the acoustic behavior of internally feeding *S. zeamais (Coleoptera: Curculionidae*) in maize. The pests were monitored for peak activity and signal amplitudes. The study was performed in the morning, afternoon and night times for three consecutive days with an ultrasonic probe attached to acoustic emission detector. The average number of peaks above threshold in the morning, afternoon and night was significantly different and were 60, 2 and 31 counts/s, respectively (P-value < 0.01). The average maximum amplitude was also different: 2.5, 1 and 1.8V for morning, afternoon and night sessions, respectively. The signal frequencies ranged between 1 and 15 kHz with a peak around 7 kHz. The second goal was to design and develop an inexpensive acoustic device for the detection of *S. zeamais* in the stored maize. This device included a microphone, signal conditioning circuit and a microcontroller. The third goal was to test the prototype in both clean and infested maize. The device could be manufactured for $55 or less. The device has a noise level below 0.2V in clean maize, infestation amplitude up to 1V and about 93.3% correct detection performance in infected maize.

DEDICATION

This thesis is dedicated to my parents (Mr. Olgen (late) and Mrs. Treza (late)) and my wife (Mrs. Tabitha) for their endless love, support and encouragement

Acknowledgement

It is my desire to thank the USAID iAGRI program for providing the grant to support me for the master's program in US and Tanzania. I wish to thank my committee members who were more than generous with their expertise and precious time. A special thanks to Dr. Kumar Mallikarjunan, my committee chairman for his countless hours of reflecting, reading, encouraging, and most of all patience throughout the entire process. I would like also to thank him for appointing me to work with him, hence realizing my dream of studying in US universities. Special thanks to Pro. Siza Tumbo who guided me throughout the research period. I would also like to thank him for his loyal heart of introducing me into his field of his expertise. Thank you Drs. Robert Grisso, and Richard Mankin for agreeing to serve on my committee. Great thanks to Mr. Everret and Dr. Richard, Entomology department (USDA-ARS-CMAVE), University of Florida for your guide in insect acoustic issues. Thanks to Mrs. Kilasara (electronic lab technician) at the electronics, instrumentation and control laboratory of Sokoine University of Agriculture who provided the support with the instrumentation. I convey my sincere gratitude to the Postharvest section manager of Ilonga Agricultural Research Institute in Morogoro Tanzania who provided the *S. zeamais* for research study. Thanks to Prof. E. Lazaro from the department of Agricultural Eng, postharvest section at Sokoine University of Agriculture who provided the support on how to keep the insects in the laboratory during the entire research period. Thanks to Nelson Richard, Werenfried, Yusto Yustas, Sneha and Stanslaus Telengia for your ideas during the proposal writing. Thanks to my friends: Dave's family, Fike's family and Steve's family for their great friendship and support during the master's coursework. Finally I would like to acknowledge and thank all the instructors at the department of Agricultural Engineering, Sokoine University of Agriculture and the Biological Systems Engineering, Virginia Tech whom I worked with during my master's program.

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CHAPTER 1: INTRODUCTION

There are several nondestructive commercial devise systems have been devised based on acoustic technology to detect insect's infestation in bulk grains (Toews *et al.*, 2003; Fleurat-Lessard *et al.*, 2006; Flinn *et al*., 2006). However, these technologies are expensive and difficult to adopt in small scale storage facilities, and consequently do not meet the needs of most of the farmers, distributors and processors in developing countries such as Tanzania (Carl *et al*., 1990, Neethirajan *et al.*, 2007). . In addition, some of these devices require computers for data analysis and are used primarily in laboratory settings with limited field applications (Fleurat-Lessard et al., 2006). The use of such computer assisted devices may contribute to significant cost increase for the farmers in developing countries as few of these farmers can afford to own computer systems. Recently there have been an introductions of new sonic and ultrasonic detection devices with headphones, (e.g., Model AED-2010 Acoustic Emission consulting (AEC) Inc., Fair Oaks, CA) which are effective in detecting and monitoring hidden insect activity through the use of a nail, steel rod, or other probes (Osbrink, *et al*. 2013). They have been useful particularly for the detection of termites, coconut rhinoceros beetles, red palm weevils, Asian long horned beetles in wood, white grubs and Diaprepes root weevil in soil, and stored products such as wheat and other grains (Mankin, 2013). Though these devices can also help in the detection of stored pests, they are expensive and need a user to listen and characterize the sound of insects through listening from a headphone. This may need trained personnel to differentiate the background noise from the insect's sound. To develop a device that can directly display an infestation level maybe very helpful to farmers. This can be achieved as proposed by shielding the background noise and using a very simple signal processing system that counts the number of times the voltage rises above the predetermined threshold level (Webb, *et al*., 1988a). Thus, may be feasible to develop portable and low-cost devices that can rapidly identify insect infestation during processing, packing, storage and selling of stored grain products in the market areas (Chambers, 2003 and Weier, 2003).

Farmers who store maize and other grains in polypropylene bags are among the key players facing a significant problem in reducing the risks of pest infestation (De Groote, *et al.,* 2013). These farmers have been suffering damages from large grain borers: *Prostephanus truncatus* (Horn) and maize weevils: *Sitophilus zeamais* (Vowotor *et al*., 2005; Omondi *et al.,* 2009; Tefera *et al.,* 2010). In addition, *Prostephanus truncatus* has been found to cause economic losses in maize worldwide (Tefera et *al.,* 2010). This has particularly found to be the case in small-scale -farm storage and in large-scale stores (De Groote *et al.,* 2013). However, the literature on acoustical behavior of this pest is limited.

In Tanzania, monitoring of these pests is done by smelling grains, observing grain temperature, observing flying insects, or noticing changes in grain color. Most of the time, the conclusion on whether bags in storage are infested is reached after emptying several bags of grains to observe some moving insects. This kind of monitoring is labor-intensive, time-consuming, and prone to cross-contamination. Such monitoring also results in costly measures in terms of buying new storage materials such as storage bags and mats as the monitoring process is accompanied with tearing of storage bags and mats due to several inspections as well as frequent handling. In some cases, contamination of even uninfested bags may occur due to the spreading of grains on a bare floor, mixing of grains and lack of procedures in separating infected and uninfected bags. These factors contribute to low grain shelf life and low profit margins from market rejection of infected grains (Kinabo, 2014). To address this problem, there is a need to develop low–cost, rapid non-destructive detection systems for appropriate use in rural areas in Tanzania. The study was then proposed to investigate the performance of acoustic based technologies for insect detection.

Objectives

Main objective

The main objective of this study was to devise, and analyze the detection performance of a low-cost acoustic system that detects insect pest infestations in stored maize under Tanzanian environmental and social conditions

Specific Objectives

I. To investigate the acoustic behavior of internally feeding *Sitophilus zeamais (Coleoptera: Curculionidae)* in stored maize
II. To design and develop an acoustic device that can detect infestations of insects in stored maize ; and
III. To test the detection performance of acoustic system in detecting the pest infestations of insect pests in stored maize

CHAPTER 2: LITERATURE REVIEW

2.1 Magnitude of pest infestation problem in developing countries

Pest infestation in stored maize is a serious problem in most of the developing countries. In Sub-Saharan Africa, maize is the most important grain staple as a source of income and of calorific intake accounting for nearly 20% of the plant-based food supply (Jones *et al.*, 2011). It is the most important staple food in Eastern Africa and the most widely traded agricultural commodity (World Bank, 2009). In Tanzania, maize stands out as the main staple food crop and which is depended on by about 85% of many farmers as an income source (Isinika *et al.*, 2003).

Maize in Tanzania is grown mostly by small farmers in various zones in a total of two million hectares or about 45% of the cultivated area (FAO, 2010). The major production zones of this crop are Southern Highlands, Lake Zone and Northern zone (Katinila *et al.*, 1998). These zones have weather conditions which favor the growth of the crop. The Southern Highlands zone has temperatures ranging from 12^{o}C to 30^{o}C, and rainfall ranging from 650mm to 1500mm while the Lake zone has an average temperature of 28^{o}C and rainfall of between 600mm and 900mm. The Northern zone has an annual average rainfall that varies from 600-1200mm to temperatures ranging from 15^{0} to 30^{0}C. This crop is mostly produced during the two rainy seasons that is, short rainy season or *vuli* (September –November) and long rainy season or *Masika (March-May)* (FAO, 2008).

Countervailing the efforts being made to maize production in Africa, lack of resistant varieties and appropriate grain storage technologies cause 20-30% losses, particularly due to post harvest pests (Mwololo *et al.*, 2010). Currently, it is estimated that 1 out of every 5 kg of grain produced in Sub Saharan Africa is lost due to pests and spoilage. As Kimatu *et al.,* (2012), quoting the FAO report on *Missing Food of 2011*, report, and this lost food is enough to feed 48 million people for 12 months. Economically, sub-Saharan Africa losses are estimated to be around $ 4 billion a year (World Bank and FAO 2011).

The major maize damaging pests in African are maize weevils (*Sitophilus zaemais*) and large grain borers (LGB) *Prostephanus truncat*us (Horn) (Vowotor *et al*., 2005; Omondi *et al.,* 2009; Tefera *et al.,* 2010). These were first found in East Africa in the 1970s and in West Africa in the early 1980s (Markham *et al.,* 1991). Currently, they are present in more than 18 African countries

(Omondi *et al.,* 2009; Tefera *et al.,* 2010). In general, the LGB are estimated to cause loses from 9 to 45 %, depending on the duration of storage (Kumar, 2002; Gueye *et al*., 2008).

Many published reports have suggested that the practice of using the traditional storage structures in Africa is conducive to loss (Proctor, 1994; Adejumo *et al*., 2007). The reason is openings in the weak storage structures that serve as the entry ports for pests (Proctor, 1994*; Ngamo, 2000; Adejumo et al., 2007*). In other words, small scale farmers typically have storage structures which are generally not hermetically sealed hence giving a room for the pest to make their way into the structure (CIRAD, 2002)

2.2 Magnitude of pest infestations in Tanzania

Tanzania is one of the East African countries in which *Prostephanus truncatus* (Horn) and maize weevil, *Sitophilus zeamais* are major pests (Rugumamu, 2004) which cause severe post-harvest losses. The losses that are caused by Coleoptera (beetles) in storage for 9 months is about 31.8% for cob corn and 7.8% for shelled maize with economic loss of 28% of the total value for cob corn and 4% of the total value for the shelled corn (Bell, *et al.,* 1999). Mallya (1992) revealed that the losses of about 35% may occur due to *Prostephanus truncatus* in 5-6 months and the losses may go up to 60% after nine months of storage (Keil, 1988) for the improperly stored corn. The losses caused by these insects may either be direct such as weight loss, reduced germination, and reduced nutritional value of grain or direct damage such as heat and moisture migration, reservoir of diseases, and distribution of microorganisms (White 1995). Some of the previous studies have found that these attacking insects have the ability of dispersing toxigenic *Aspergillus flavus* that facilitate aflatoxin in grains (Nesci *et al*., 2011a, b).

Farmers have been trying to identify cost effective post-harvest technologies which can minimize the damage of the grain that occurs due to pest infestation during storage. Currently, farmers minimize the damage by relying on a mix of conventional and synthetic grain protectants. In addition, they use a varietyof storage structures for storing grains: sacks, baskets and cribs as well as mud brick silos, underground storage pits, and earthenware pots and gourds. Other storage methods/structures include: suspension of crops on a tree or above the fireplace, roof storage, silos [metallic or concrete] and air tight plastic bags (Mboya, 2011). These kinds of traditional storage practices cannot guarantee protection of a staple food crop like maize (Tadele *et al*., 2010). In addition, global increase in temperatures is expected to accelerate the rates of pest in tropical and subtropical areas, temperature being the single and most important regulating factor for insects (Petzolet and Seaman, 2010). All these factors will likely continue to pose challenges to farmers in containing pest infestations as well as forcing them to sell surplus grains at the lowest prices soon after harvest. They will do so in order to curb the losses by post-harvest hazards and partially to meet other financial needs (Kimenju *et al*., 2009).

2.3 Existing technology on grain monitoring

Different means of monitoring grain storage units are used in different parts of the world. For example researchers have discovered use of microwave-radar (Termatrac) that has heat treatments (Mankin et al. 1999) and electrical stimulation (Mankin 2002) to increase the activity and acoustic detectability of insect larvae. However, such treatments had limited applicability (Mankin, 2006). The low applicability of these types of microwave- radar was due to the continuing interest in finding best way of reducing the incorrect ratings of low likelihood of infestation ie "False negatives" (Mankin et al., 2006). Researchers have used this microwave-radar detection technology to detect the hidden insects of different sizes and activity levels in stored product packages of maize meal mix and flour mix. In this technology, movements of individual adults or groups of *Lasioderma serricorne* (F.), *Oryzaephilus surinamensis* (L.), *Attagenus unicolor* (Brahm), and *Tribolium castaneum* (Herbst) were easily detected over a distances of up to 30 cm in the stored products (Mankin, 2004).

Acoustic tools were also used in testing the performance of termiticide time required to kill the termites after the application of termiticide against the termites in dry forage (Barwary, 2013). In this study, the treatment units were monitored for termite movement by utilizing Termatrac T3i tool until no movement was detected. It operated by emitting a beam of fixed frequency and displayed the time-variation of differences between the emitted and reflected signals from the collected receiver to the panel liquid crystal display (LCD) at a distance (Tirkel et al., 1997, Protecusa, 2002). The tool indicated the ceasing of termite movement at day 5 and 7 for the 0.30 and 0.15 mg dosage effects, respectively while working at a distance.

Another study was done to increase the performance of detecting the larvae feeding internally in the wheat grains. This was done by establishing the guidelines and procedures for shielding of an acoustic system inside the wheat grain elevator. The sound pressure level (SPL) generated by rice weevil such as *Sitophilus oryzae* (*Coleoptera: Curculionidae*), larvae in wheat kernels is only 23 dB. Thus it was recommended to shield the grain being tested and attenuate background sound by 70-85 dB (Mankin, et al., 1996).

Also, another study counted the insects in 1kg of wheat grain sample using an acoustic system. In this study, the detector was used to analyze the input from the ray of sensors fixed into the walls of a sample container. The study results revealed that the level of sound produced by insects was proportional to the weight of insects (Mankin, et al., 1997).

The infestation in grain commodities was also studied by inserting the piezoelectric probe sensor into commodity (Litzkow *et al*., 1990). In this study, the piezoelectric sensor was used to detect vibrational frequencies above 500 Hz within the agricultural commodity. The device was found to be able to capture the insect's vibration whenever the frequency of these insects were above 500Hz. This invention was recommended to be utilized in grain commodities such as rice, nuts, wheat, cotton as well as maize.

Studying the infestation in the agricultural commodities was also conducted in an isolation structure (Hickling 1997). The grain commodity was placed inside the isolation box to isolate it from the external field noise and vibration. The detected sound from the sensor in the box was recognized as an output in the earphone or light emitting diode. However, this system was designed to detect sounds of pink bollworm and other larvae that can be inside the cotton bolls or fruits. The use of a single or multiple sensor arrays was recommended to test the apparatus in other commodities which could be separated individually

2.4 Insect sound transmission in grains

Hickling (1995) conducted a study on sound transmission in stored grain, with the aim of facilitating the use of microphone in pest detection. The study was done by inserting the sound source (speaker) inside the 5-m iron tank of wheat grain. The study results found the sound to be transmitted principally through the air passage inside the grain at the frequency of 1 KHz over a distance of 1 m. However, grains are highly absorbing acoustical medium (Hickling *et al*., 1995). They act as a low-pass filter, with the attenuation coefficient increasing roughly as the square root of frequency. The strong absorption of the grains may lower background noise, but it also limits the range over which sounds of insect activity can be detected (Hickling *et al*., 1996). In addition, due to differences in inter-kernel spacing, sound transmission may vary with the type of grain (Hickling *et al*., 1996). Also, the speed of sound may vary with respect to the softness and hardness of grains. This was also found by a study on speed of sound in soft wheat under different gases: air, argon and carbon monoxide and was found to be 347, 334 and 271 m/s respectively (Hickling *et al*., 1996).

2.5 Disease associated with maize weevils and large grain borer

Apart from spoilage damage, insect often are vector disease organisms. Maize weevils are carrier of numerous fungi species such as *A. niger, A. glaucus, A. candidus, Pencillium islandicum, P. citrinum, Paecilomyces, Acremonium*, *Epicoccum*, *F. semitectum* and yeast (Smalley, 1989 and Dix, 1984). In addition, hairy fungus weevils have also been noted as the carrier of *Salmonella enterica serovar* Infants and are capable of transmitting it over long distances (Hold *et al*., 1988).

2.6 S.zeamais Life cycle

The average life cycle of *S. zeamais* is 35 days at 27^{o}C (Sharifi, 1971b), increasing to 110 days at 18^{o}C. In addition, it is an insect which is estimated to have higher survival ability when habitat temperature is approximately 25^{o}C. *Sitophilus zeamais has the ability to* lay more eggs at 60% relative humidity together with the ability to hatch 90% of its eggs in supportive environments, although 30% mortality of this production can occur at relative humidity of 50% (Arbogast, 1991)

Sitophilus zeamais distribution

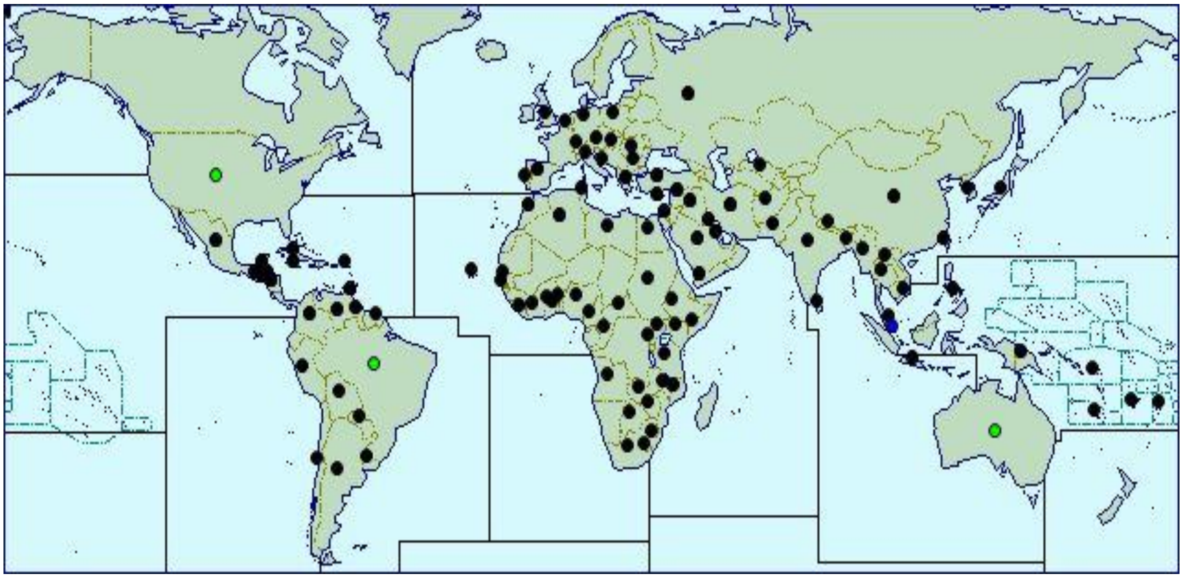


Figure 1 : Distribution map S. zeamais (source: http://www.cabi.org/isc/datasheet/10926)

 = Present,

 = See regional map for distribution within the country

CHAPTER 3: MATERIALS AND METHODS

3.1. Specific objective: Investigation of acoustic behavior of internally feeding *Sitophilus zeamais* (Coleoptera: Curculionidae) in Stored Maize

3.1.1 Data collection

Sitophilus zeamais larvae were obtained from an infested maize colony at Ilonga Agricultural Research Institute in Morogoro, Tanzania. The samples of infested maize kernel (25-ml) were held in a perforated plastic bottle (1L) during the period of conducting the experiment. Two clean stainless steel sheet containers were prepared and each was filled with 3kg of clean maize. The 25-ml of *S. zeamais* in a perforated plastic pouch of 100mL was put in one of the container to make it infected while the other container remained clean to make a reference of uninfected maize. The number and age of insects were about 78 adults (3-4 mm length, dark brown color, with four reddish stains on the elytra,) and 26 larvae (light yellow in color with a darker head) during the experiment. The larvae were counted by inspecting weak skin on the maize kernel and cracking the grain.

The sex and the instar level were not considered in this experiment as the experiment aimed at the detection of few insects. However, some other studies on insects such as beetles have found no sex-related differences in insect's sound (Hall et al., 2013).

To collect sound signals in the stainless steel sheet container, a 15-cm-length waveguide (probe) was attached to a sensor/preamplifier (Model SP-1L, AEC Inc., Sacramento, California, USA) of an acoustic insect detection system (Model AED-2010, AEC. Inc.), hereafter called the standard device. The signal from the AED-2010 was then transferred to an Analog to Digital convertor - (ADC 200/20, Virtual Instrumentation for windows, Max 20V, and UK. model) based Pico-oscilloscope to display the captured signal on the computer screen. The ADC was set to collect 2442 voltage samples in 1 second. The method used to collect the observed pulse activity was to stop the running signal on the computer screen whenever an activity was noted. During the experiment, the probe had to be shifted from the infested container to the clean container after every 10 runs in either of the container in order to get nearly the same background noise consistently. To reduce external noise in the container, the container inlet was plugged with rubber material after inserting the probe sensor. The data were recorded at three sessions: Morning sessions (8:00 – 11:00 am), Afternoon (1:00-4:00 pm) and Night (7:00-10:00 pm). Each clean and infested maize had a record of 54 samples with respect to three recording sessions. The records were taken for three consecutive days using the same procedure. The following is the instrumentation layout during data collection.

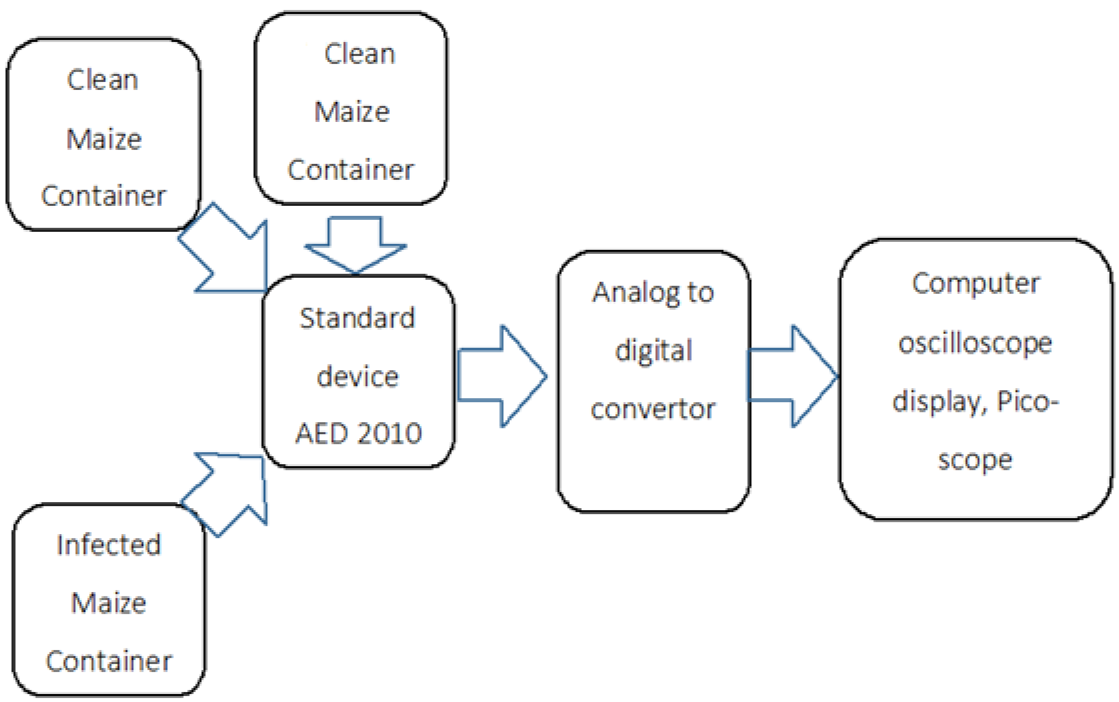


Figure 2: Instrumentation layout for data collection

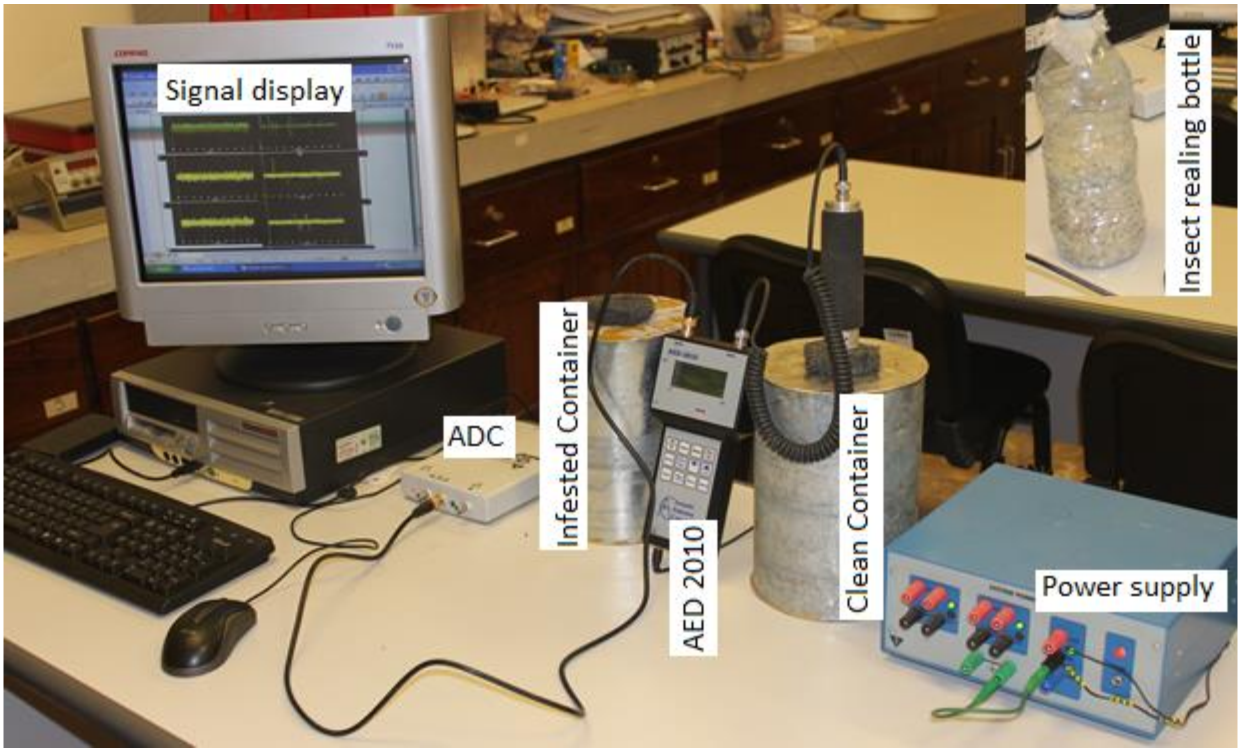


Figure 3: Photo on tools used for data collection

3.1.2 Differentiating the noise and infestation by AED- 2010 - device

Because the experiment was conducted in a controlled laboratory environment, the signals in the infested maize container that were greater in amplitude than the threshold reference level in the clean maize were assessed as the *S. zeamais* activity, as discussed in Chapter 4.

3.2. Specific objective: Design and develop of prototype acoustic device that detects the insect' in stored maize

3.2.1 Prototype design procedures

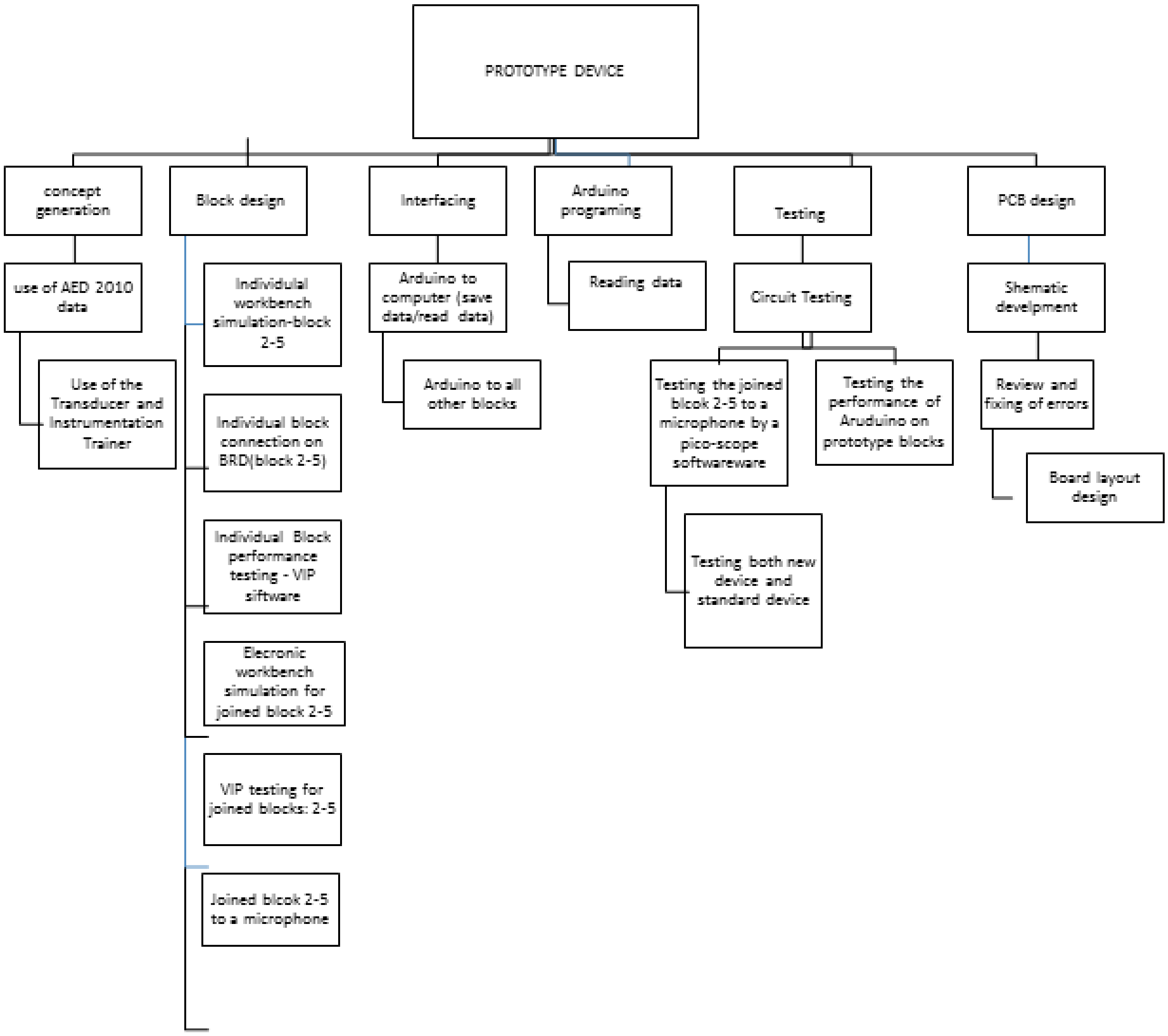


Figure 4: Procedure on designing and developing an acoustic prototype device

3.2.2 Concept development with Transducer and instrumentation trainer (TIT)

The procedure for developing a prototype was first drafted and tested on the Transducer and Instrumentation Trainer (DiGiAC 1750, UK model). The circuit instruments on the instrumentation trainer included a microphone, AC amplifier, full wave rectifier, amplifiers 1 & 2, L.E.E bar- graph and a moving coil meter. The AC amplifier gain control was set to 1000; then gain- of amplifier #1 and #2 were tested from 1 to 10. The amplifier #1 and #2 gain-fines were also set to 1 while talking, or whistling near the microphone unit to create a signal input. The signal output were observed on the LED bar- graph display that required a 0.5V increase to light each additional bar (5V to light up the full bar). A moving coil meter was also used as a peak power meter (PPM) to indicate the peak voltage.

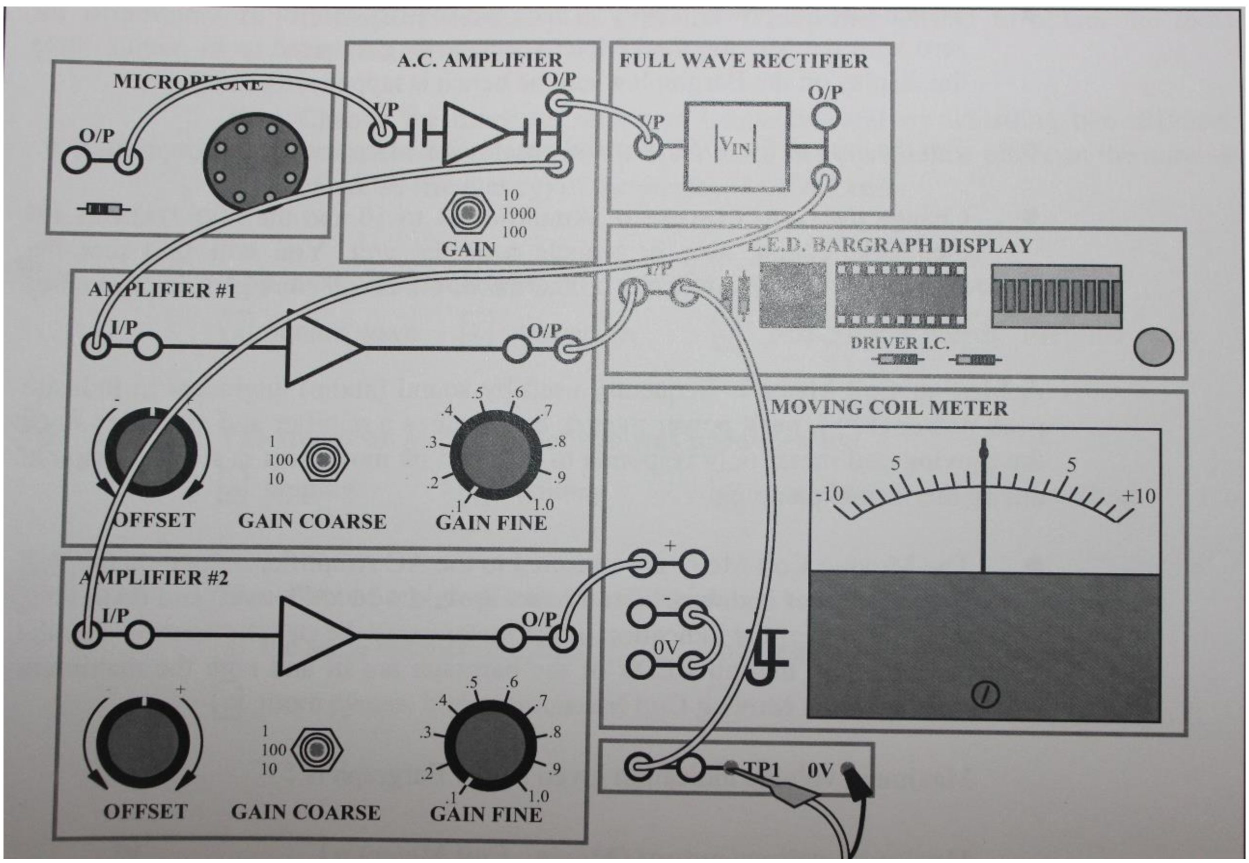


Figure 5: Testing the prototype design layout using the Transducer and Instrumentation trainer's electronic components

3.2.3 Prototype layout, design and testing

Based on the results from the Transducer and Instrumentation Trainer above, the prototype was designed with seven main block components (Noise-filter, amplifier, voltage regulator, micro-controller and the display uni

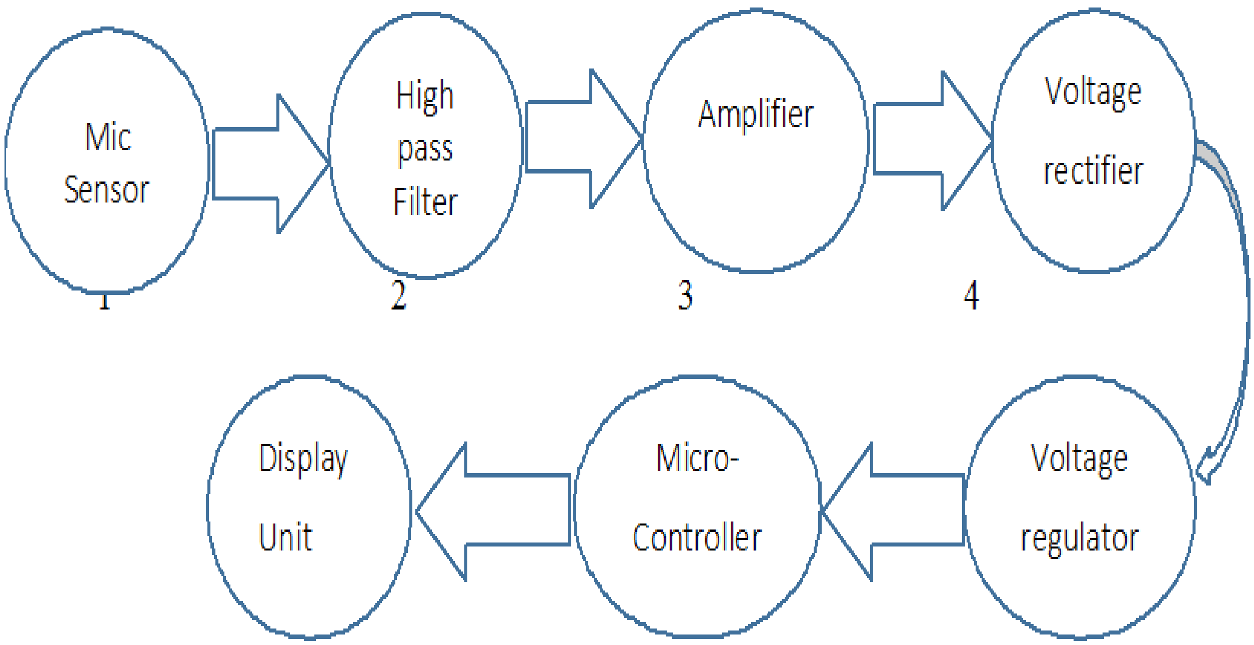


Figure 6: Main Prototype components

The electronic circuit design for the first four components included the setting of input and frequencies using the electronic workbench simulation software (EWSS) version 2. The testing of the physical circuit components on the breadboard (BRD) was done by passing signals with known frequency into the block component using the Virtual instrumentation Platform (VIP): DIGIAC3000 data Server with a serial # D3000 VIP Mk2, board # D3000-4.3. Each component block was designed and tested on separately before assembling the components

3.2.4 Design and testing of circuit components

Design of High-pass filter circuit component

The filter design was the active Butterworth High-pass Filter with a Unity Gain in the Passband, 24 dB / Octave and 2 x 2nd order. The circuit and its component values (capacitors and resistor values) were obtained using an open source calculator at (http://www.changpuak.ch/electronics/Butterworth_Highpass_active_24dB.php). The circuit was designed to have a unity gain and to attenuate all frequencies below 1 KHz as the system noises. However, the workbench simulation showed this filter circuit to also attenuate at 85 KHz.

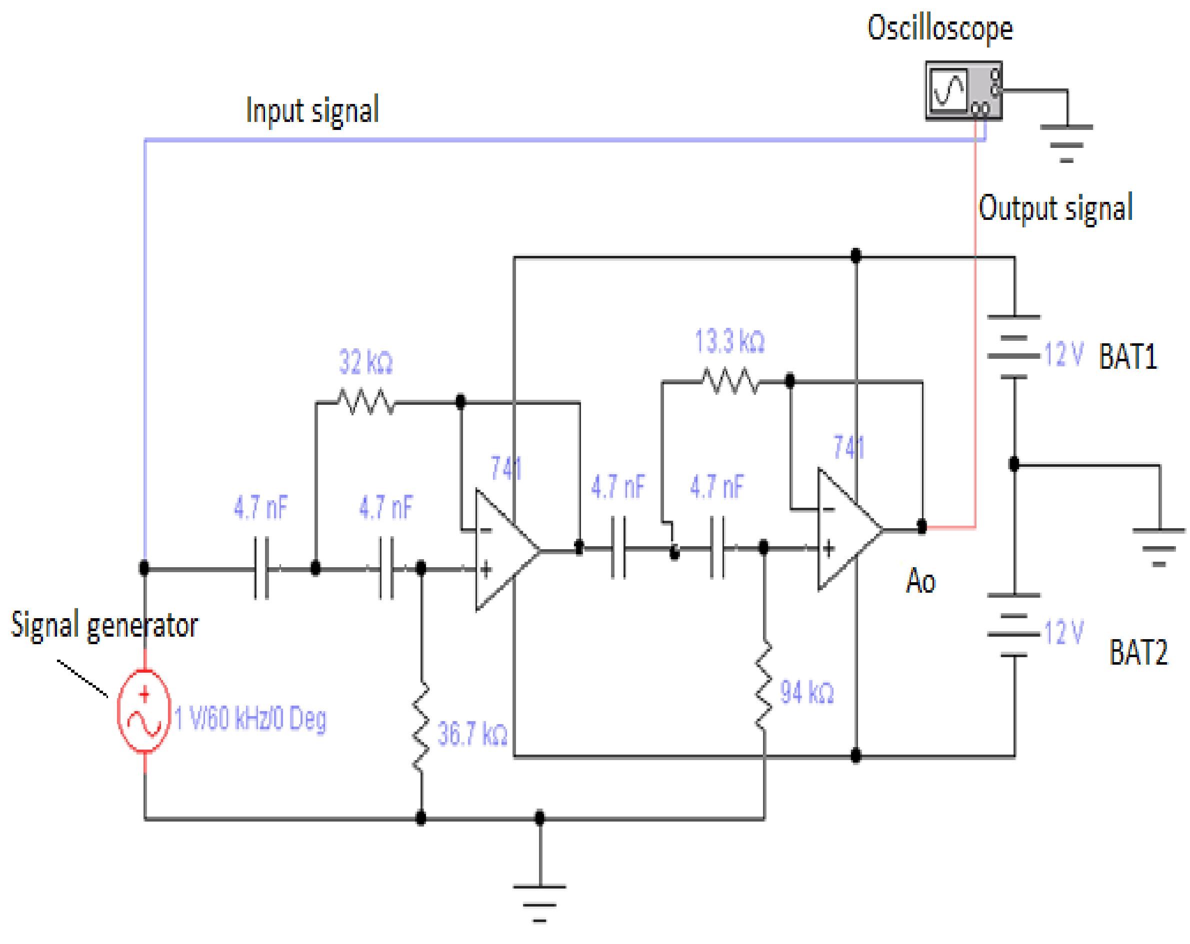


Figure 7: High pass filter circuit.

(a) Simulation and testing of High-pass filter circuit with Electronic Workbench Software (EWS)

Blue color: Input signal Red color: output signal

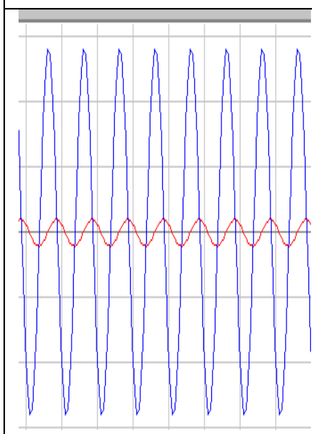


Figure 8: 0.5kHz, highly attenuation of output signal

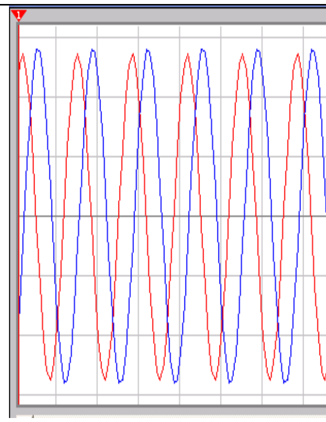


Figure 9: 1.5kHz, there was a partial attenuation of signal output

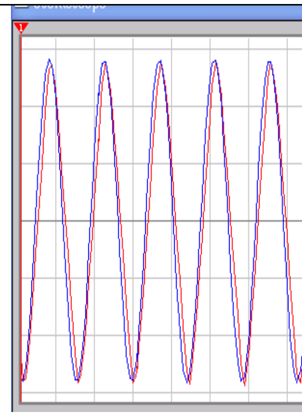


Figure 10: 70kHz, No signal attenuation

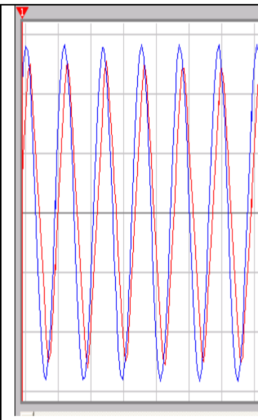


Figure 11: 85kHz, partial attenuation of signal output

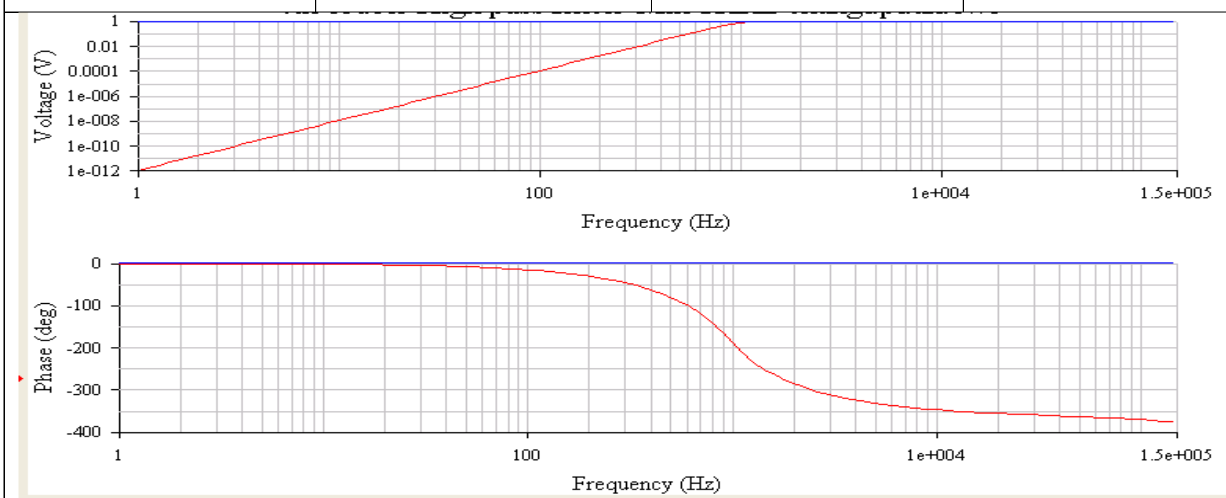


Figure 12: AC frequency response in log scale, the output voltage was found to be 1V at the f 1kHz. The input and output signal were found to be in phase at the frequency around 1kHz.

By simulating the theoretical circuit in the EWS, all output signals at node A_0 that were less than 1 kHz were found to attenuate (Fig. 8 and 9). These included most of the signals that were regarded as the noise from the system. This was also observed at the AC frequency curve (Fig. 12). The High pass filter was found to perform well in the range between 1 and 70 kHz as shown in Fig. 4c. The output signal started to attenuate at 85 kHz (Fig. 11).

(b) Physical High-pass filter Circuit testing with the Virtual Instrumentation Platform (VIP)

Descriptions: White color Signal: output at 0.5V per division, Yellow color signal: input signal at 0.5V per division and Slope: -20dB

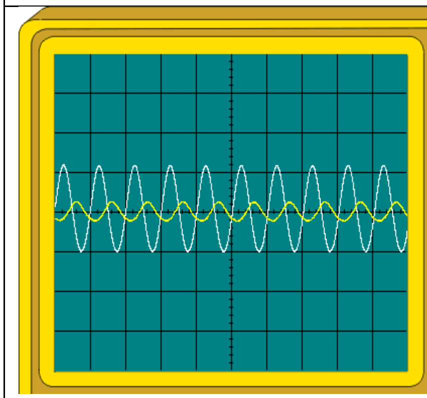


Figure 13: Generating frequency at 1 kHz

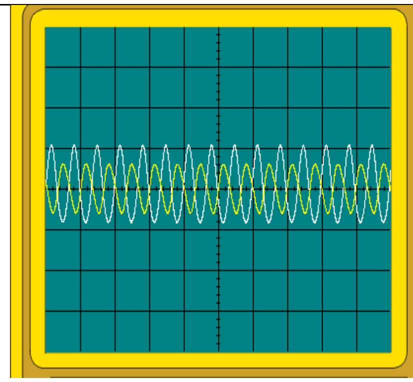


Figure 14: Generating frequency a 1.5 kH

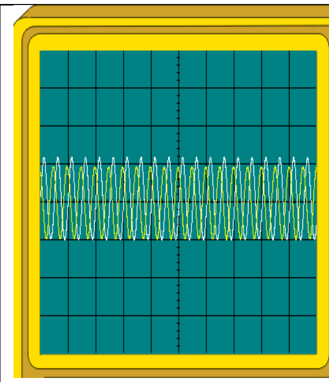


Figure 15: Generating frequency at 2 kHz

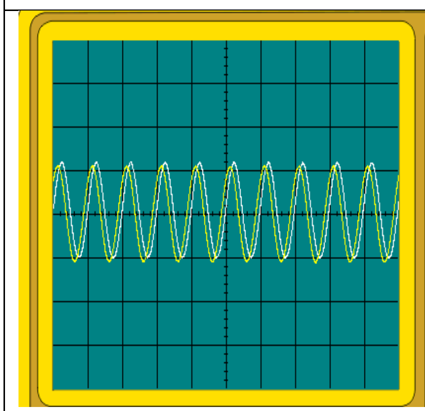


Figure 16: Generating frequency at 10 kHz

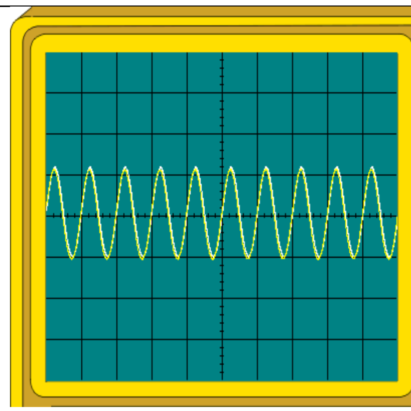


Figure 17: Generating frequency at 20 kHz

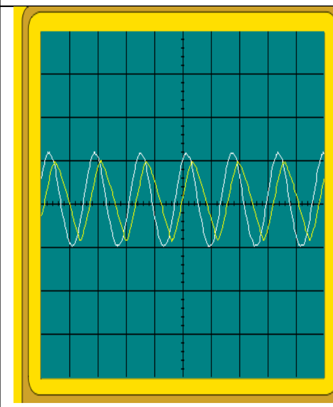


Figure 18:Generating frequency at 300 kHz

The high- pass filter physical circuit component was found to perform well in the audible frequency range between 2 and 20 kHz as the input signal was little changed in phase relative to the output signal (Figure 15 to Figure 17). This is the range in which the insect activities were expected. In addition, there was a difference between the simulation results of the EWS (theoretical circuit testing) and the VIP (physical circuit testing) in terms of attenuation points in the highest frequencies. The simulation results of the theoretical circuit had attenuation at 85 kHz (Figure11) while the simulation for the physical circuits attenuated at 300 kHz (Figure. 18)

Design of amplifier circuit component

(a) Simulation and testing of amplifier circuit with Electronic Workbench Software (EWS)

This was done in order to approximate the circuit resistance parameter that is necessary to make the optimum voltage gain (ratio of output voltage to input voltage).

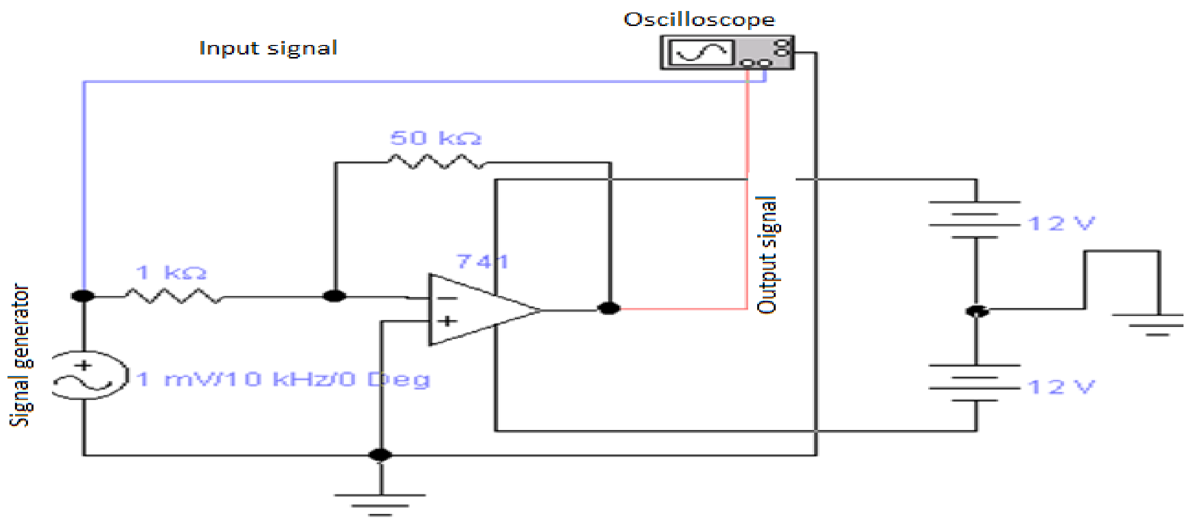


Figure 19: Amplifier circuit component for detection of insects with High gain microphone

The amplifier was tested for its ability to amplify weak input signal. The optimum amplification factor was 50 when detecting the input signal from the Super High Gain microphone sensor (0.23" L x 0.70" W x 0.31" H, 20-160000Hz frequency response, S/N Ratio more than 58dB, 6-12V, 20mA power, Impedance 150 a ohms at 100Hz). This was accomplished by using a single stage amplifier (LM 741 CN) as shown in Fig.19. However, when using the ultrasonic probe (Model SP-1L, Acoustic Emission Consulting [AEC] Inc., Sacramento, California, USA) of an acoustic insect detection system (Model AED-2010, AEC. Inc.), the optimum amplification factor required was about 100. This required a two stage amplifier circuit. Since the prototype was expected to reduce the overall cost of detecting infestations, the use of the microphone was an important feature of the prototype as it needed minimum amplification and it was inexpensive ($6.00, source: http://www.spyassociates.com/product/super-high-gain-microphone-audio-system) compared to the cost of the sensor probe ($500).

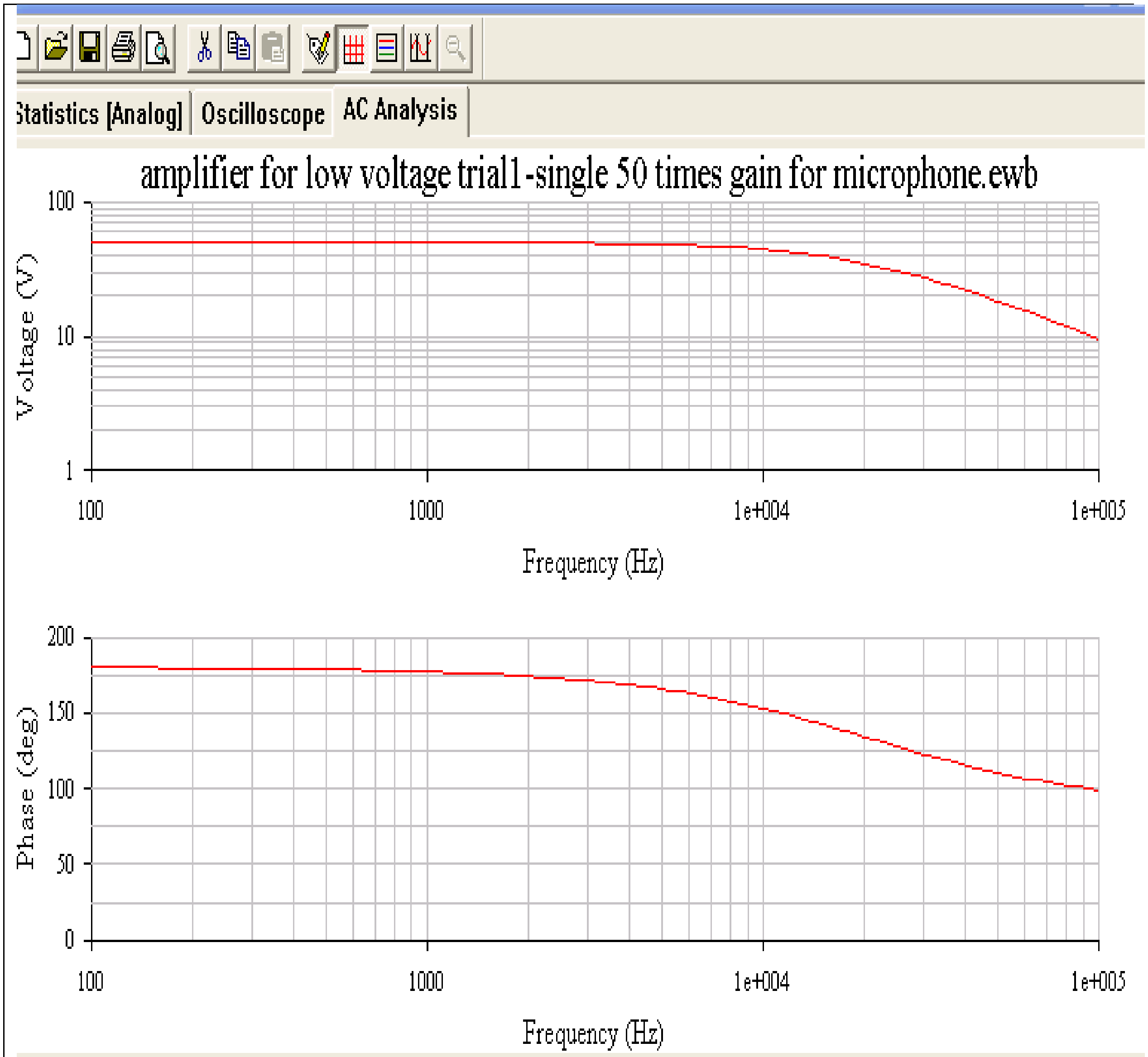


Figure 20: frequency response of a microphone system; the output voltage attenuated at 20f kHz. The input and output signal were found to be in phase in all frequencies

Considering Figure 20, the amplifier circuit performed best in the audible range. The output signal exhibited attenuation at 20 kHz. However, the circuit continued to provide some amplification above 20 kHz.

(b) Simulating and testing the physical amplifier circuit with a VIP instrument.

Description: The input signal (white signal) is scaled at 0.1V/div while the Output Signal is scaled at 10V/div.

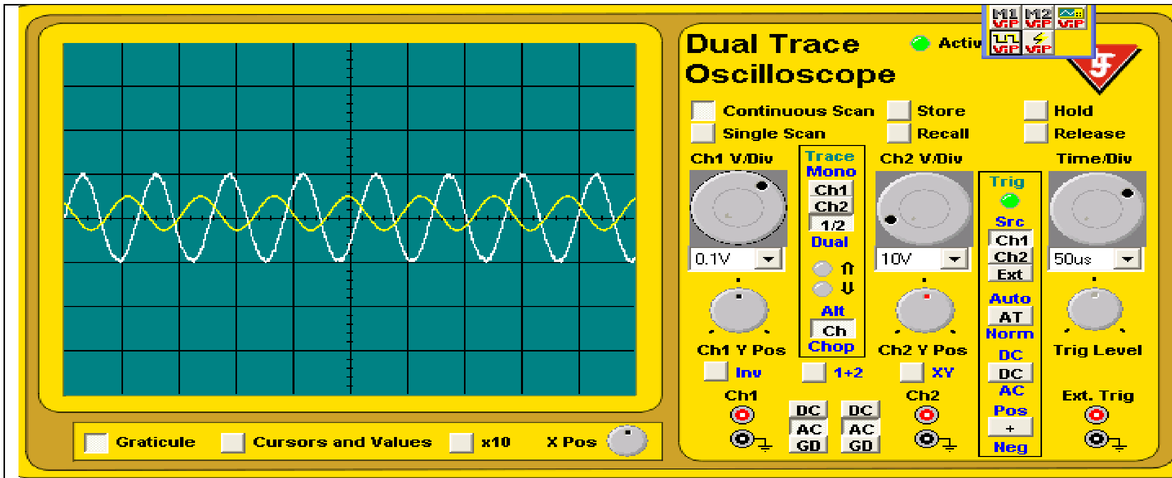


Figure 21: Example of signal amplification at 1.5 kHz. The output was the same to this one for any input signal between 1 and 24 kHz.

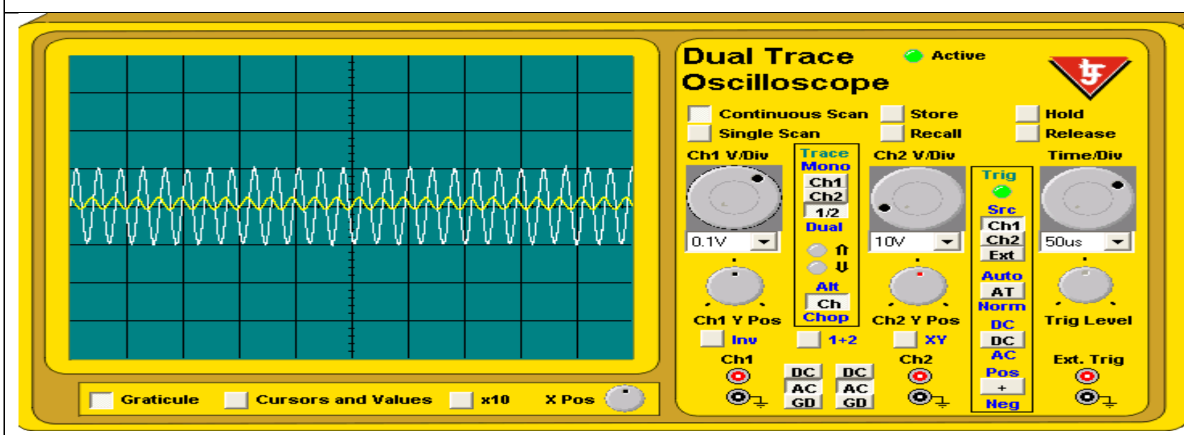


Figure 22: Example of signal amplification at 26 kHz. The output signal was nearly like this one for any input signal between 25 and 50 kHz.

In Figure 21, the input signal (white signal) at 0.1V was multiplied by 50 times by an amplifier to form an output signal (Yellow Signal) with 5V. The amplifier was tested and was found to have the same performance between 2 and 24 kHz. However, at higher frequencies (25 to 50 kHz), the input signal with 0.1 V was amplified by only 20 to form a 2V output signal as shown in Figure 22.

Testing the filter and amplifier performance

(c) Simulation and testing both filter and amplifier circuit with Electronic Workbench Software (EWS)

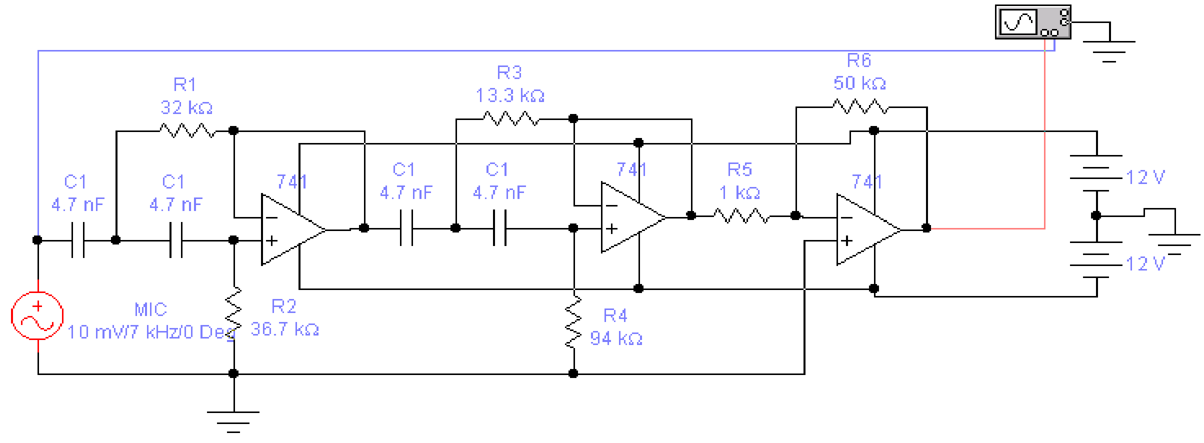


Figure 23: Circuit diagram for the connection between the high pass filter and the amplifier

(d) Simulated input and output wave forms

Description: Input signal (Blue): 5V/div, Output signal (Red): 5V/div

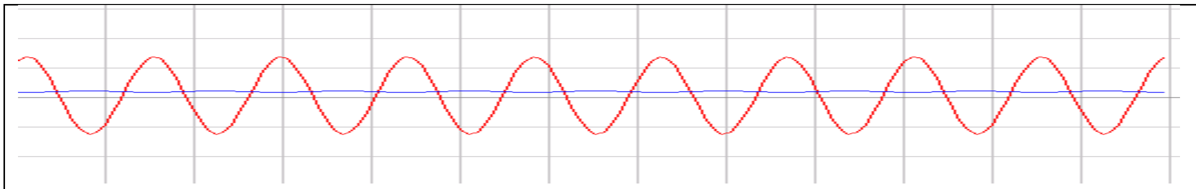


Figure 24: Circuit testing with the input voltage at 100 mV

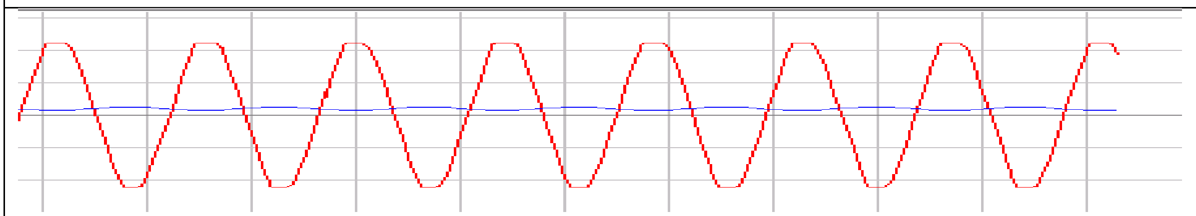


Figure 25: Testing with input voltage greater than 100 mV

Considering Figure. 24 and Figure.25, both filter and amplifier circuit performed better fidelity when the input voltages were below 100mV (Fig.24). The circuit voltage saturated when the input voltage was greater than 100 mV (Figure 25). In other words, the system maybe unusable when the input signal has the voltage beyond 100mV.

(e) Simulating and testing connection of physical filter and amplifier circuits with a VIP instrument.

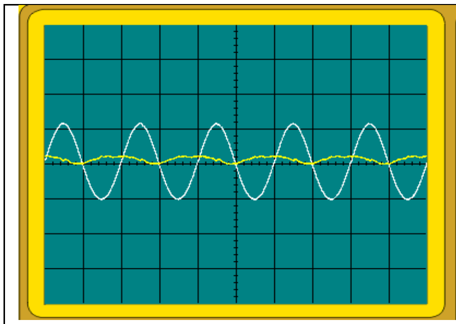


Figure 26: Example of output signal when the input signal is at 0.8 kHz. All signals less than 1kHz were attenuated

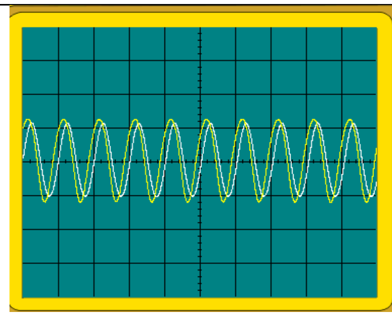


Figure 27: Example of the output signal when the input signal is at 1 kHz

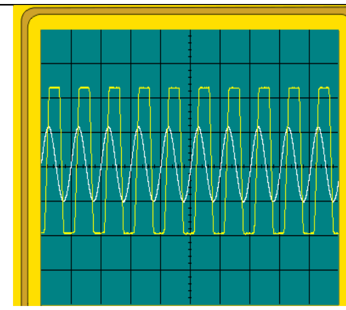


Figure 28: Example of input signal at 2 kHz. The output signal was nearly same up input signal of 10 kHz

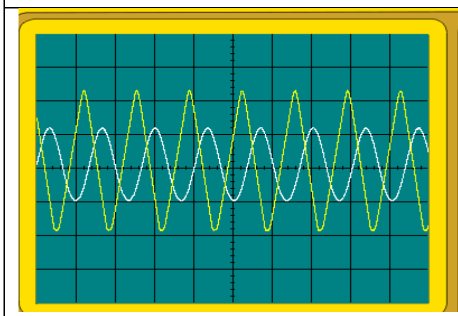


Figure 29: Example of output signal when the input signal is at 13 kHz. The output signal was nearly the same up to input signal of 20 kH

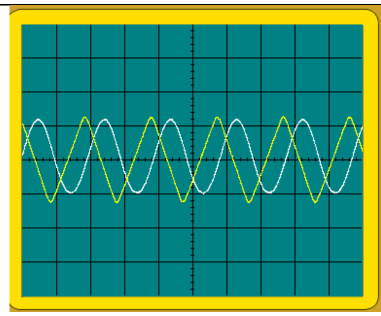


Figure 30: Example of output signal when the input signal is at 2 kHz. The test had similar output up to input signal of40 kHz

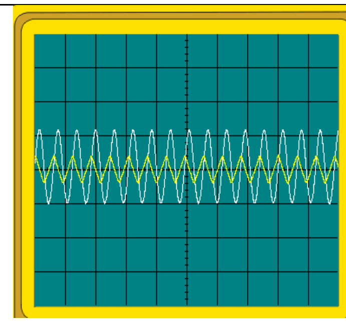


Figure 31:Example of the output signal when the input signal greater is than 40 kHz

Looking at Figure 26 to Figure 31,, the input signals with the frequencies less than 1 kHz were not amplified (Figure.26) while the signals at 1 kHz were amplified to 5V (Figure.27).The output signal ranging between 1 and 10 kHz were highly amplified (Figure.28).This was considered beneficial as the insect's sound were expected to have relatively high energy in this range. The input signals between 10 and 20 kHz were moderately amplified to 10 V (Figure 29), the input signals within the frequency between 20 and 40 kHz were amplified to 5V (Figure 30) and the one in the frequency greater than 40 kHz were amplified nearly to 2.5V (Figure 31). However, the output signals lagged the input signal in all situations.

Design of a rectifier and voltage regulator

Design and workbench simulation of a unity gain full wave rectifier circuit

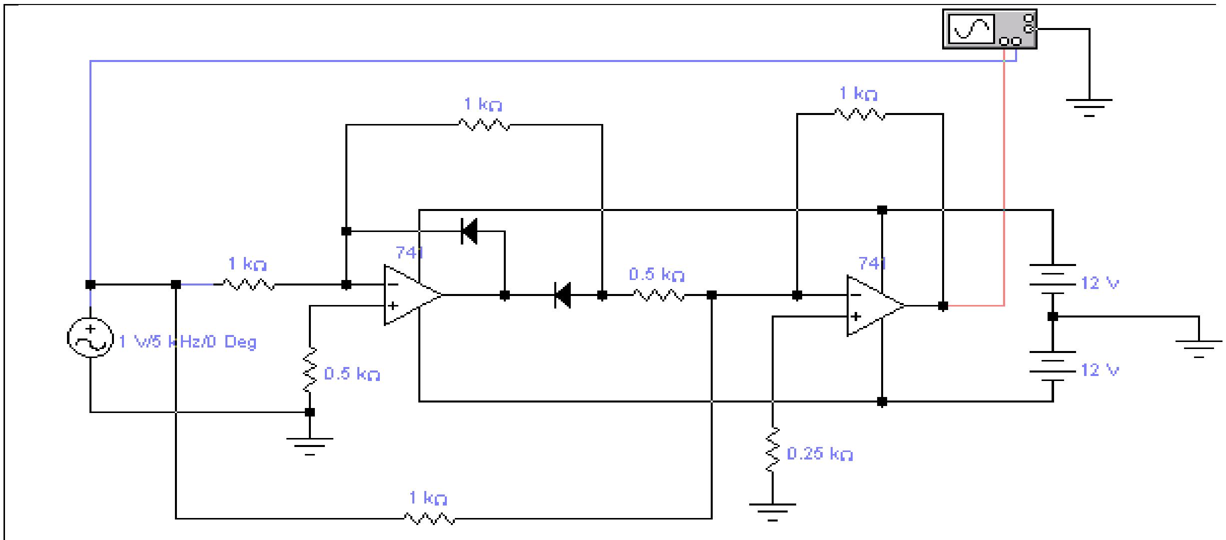


Figure 32: Full wave rectifier circuit before capacitor coupling

This was designed in order to change the negative signal into positive signal (DC signal) to accommodate the range of the Arduino UNO Micro controller.

a) Signal output for a theoretical circuit in the EWS.

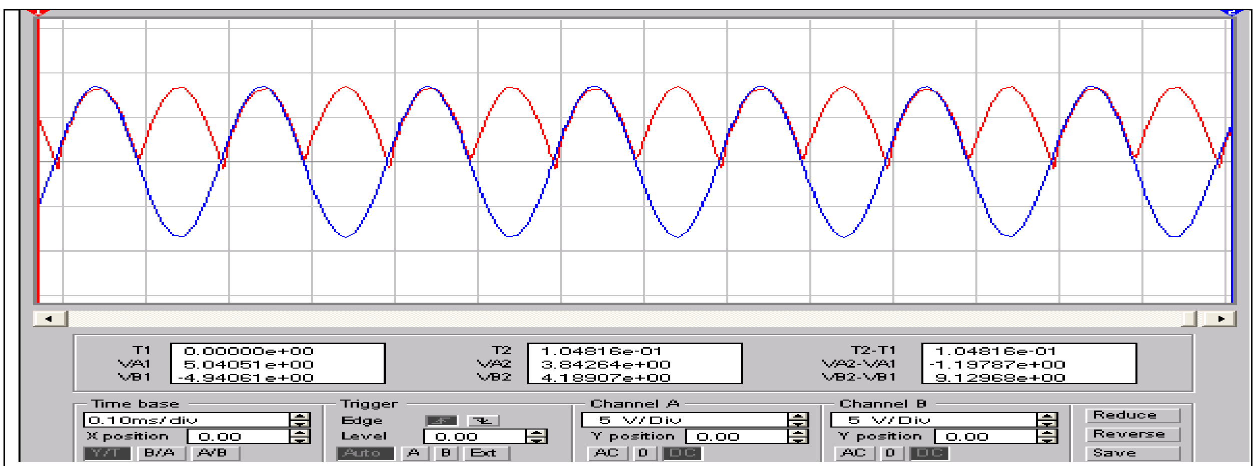


Figure 33: Wave forms for input (Blue signal) before rectification and Output (Red signal) after positive rectification

The results signal output when testing the physical voltage rectifier on the breadboard using the VIP

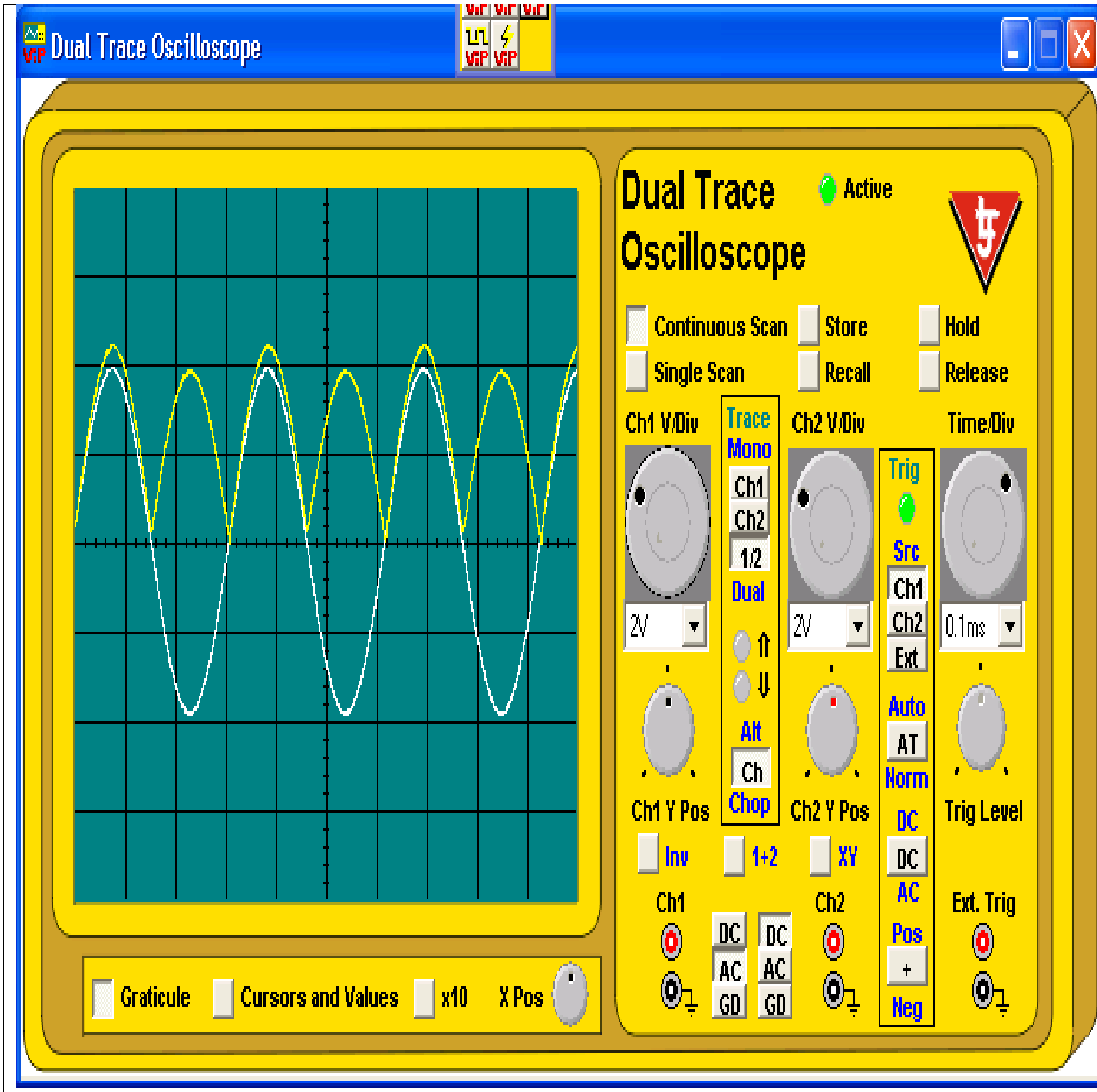


Figure 34: Wave forms for physical rectifier circuit on the breadboard before wave smoothing

b) Smoothing the full wave rectifier signal outputs

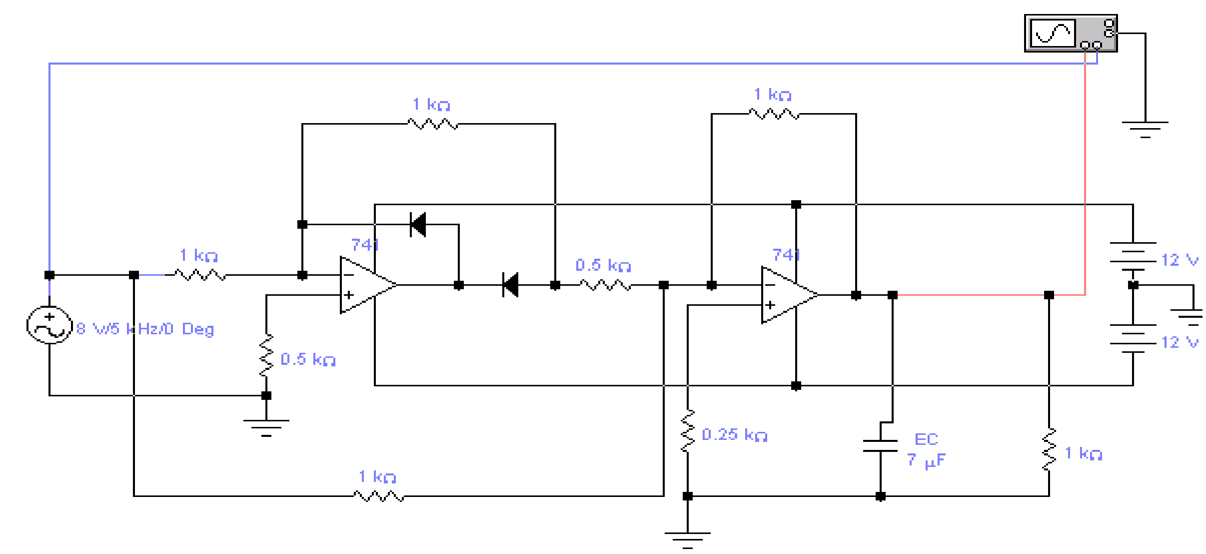


Figure 35: Full wave rectifier coupled with a smoothing EC and road resistor RL for signal smoothing.

The full wave rectifier in Figure 35 was then coupled with an electrolitic capacitor (EC) and road resistor for signal smoothing

c) Resulted wave forms for a simulation of the smoothed full wave rectifier in the EWS

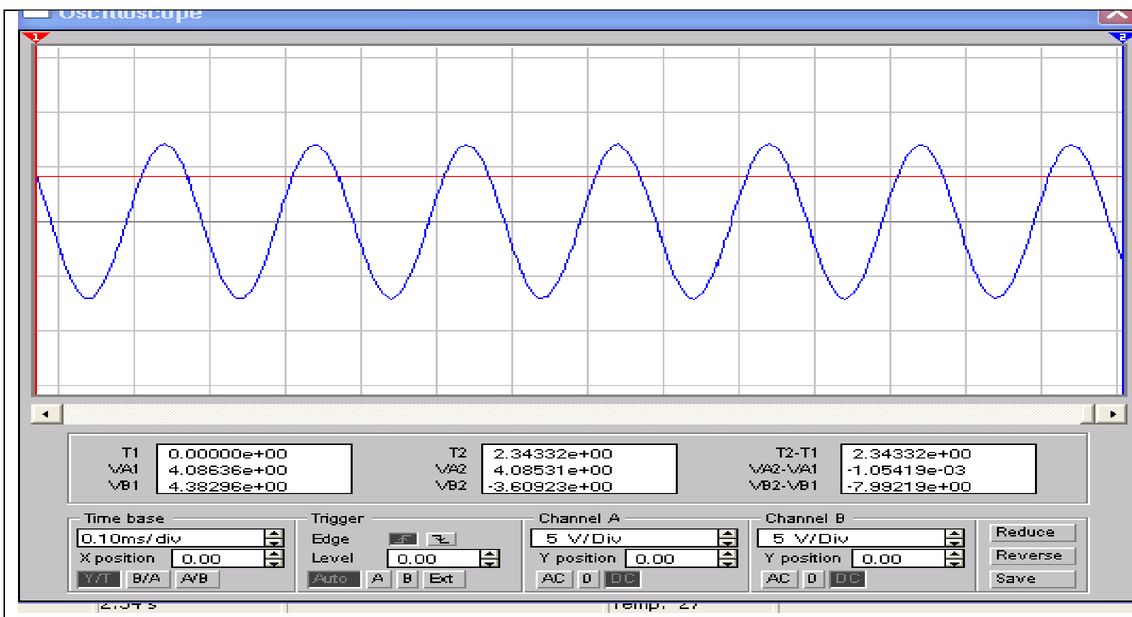


Figure 36: The signal output (Red Signal) in Figure.33 was smoothed to make DC voltage represented by a straight line in this figure.

d) EWS and VIP simulation for both smoothed full wave rectifier and voltage regulator

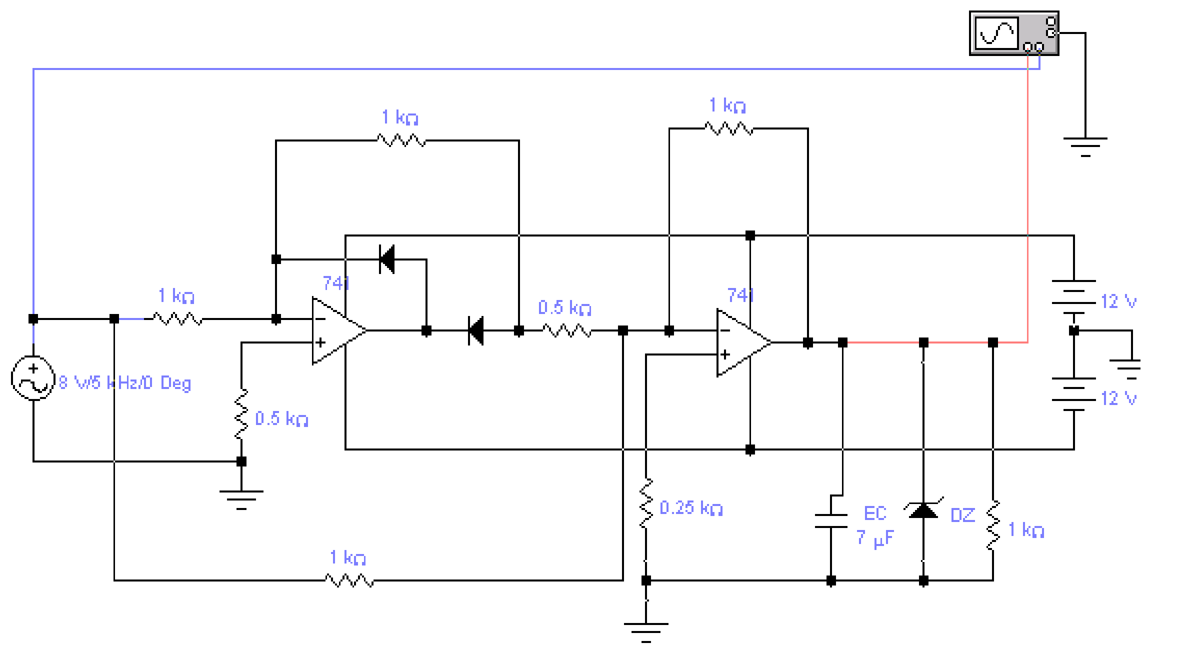


Figure 37: The smoothed full wave rectifier coupled with a zena diode (DZ, 4.7V) to limit any voltage greater than 5V to Arduino UNO microcontroller.

Description: Both Input signal (Blue) and output signal (Red) were scaled at 5V/div.

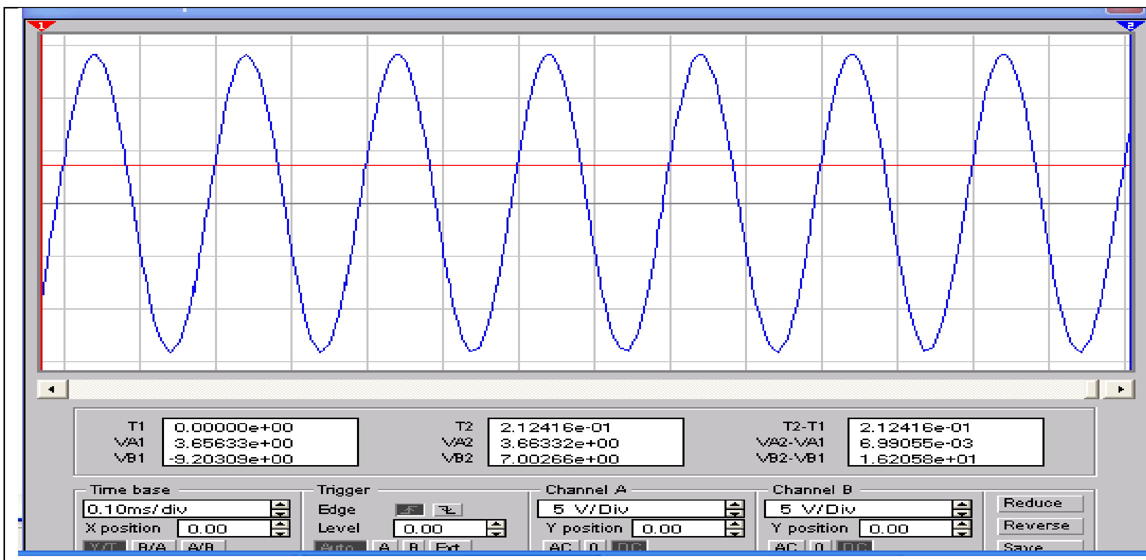


Figure 38: Example in EWS of 15V input lowered to 4.7V output by the voltage regulator

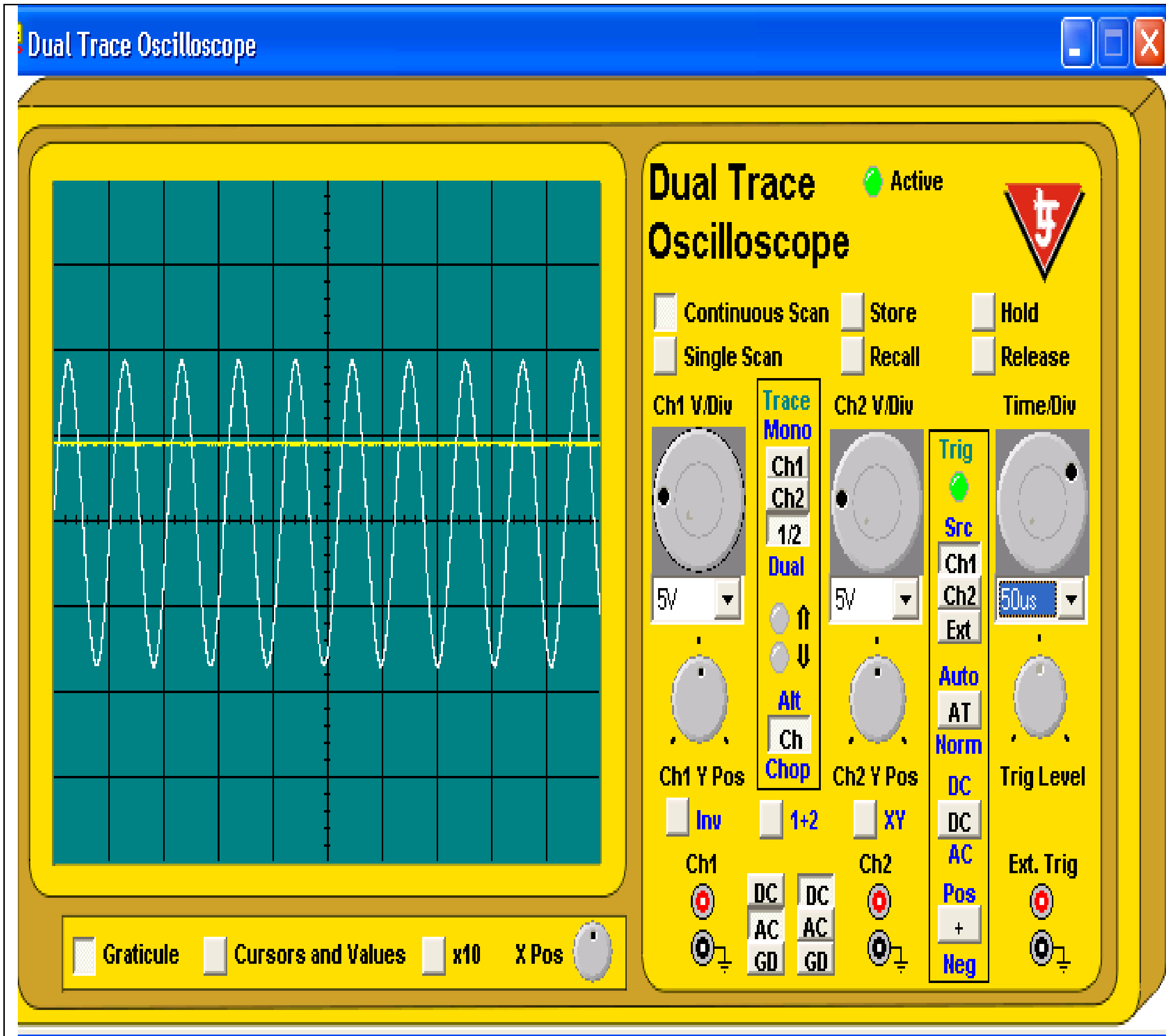


Figure 39: Example in VIP of 15V input lowered to 4.7V output by the voltage regulator

The voltage regulator was able to receive an input voltage of 15V and reduce output voltage to 4.7V as shown in Figure 38 and 39.

Assembling of circuit components on the breadboard

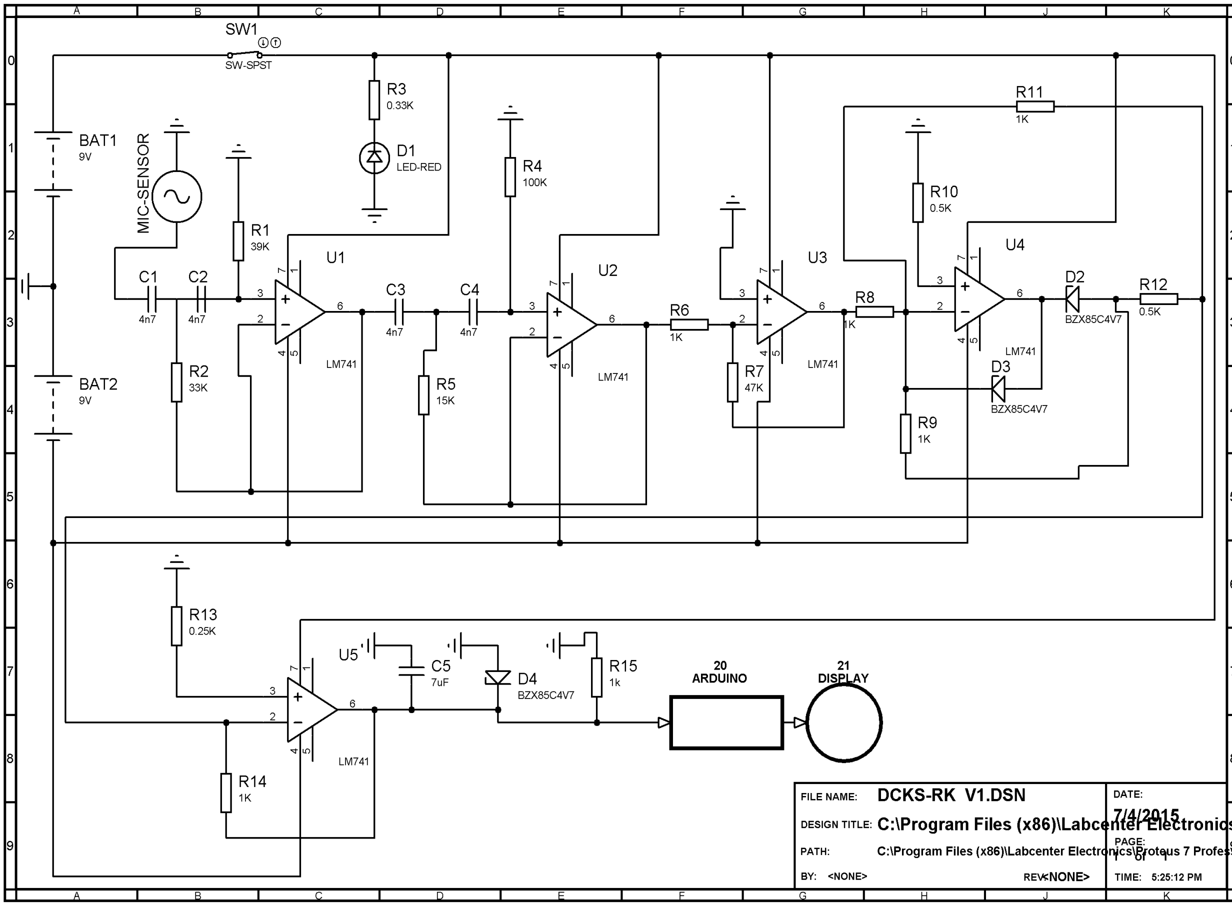


Figure 40: Prototype insect Acoustic detection system components assembled on breadboard.

All circuit components (Microphone, filter, amplifier, voltage rectifier and the voltage regulator) were assembled on the breadboard for testing with the insects before printing the Printed Circuit Board (PCB). In addition, toggle switch (SW1) was included with an LED (D1) l to indicate the presence of power supply when the switch is ON

Design of a Printed Circuit Board (PCB)

The PCB design was done using the Labcenter, Proteus 8 Professional v8.2 SP2. All circuit components were drawn in iSiS part of the Labcenter to make the schematic drawing for simulation. After the simulation, the schematic was switched to the ARES program of the Labcenter to make a PCB board.

(a) Simulation of Schematic diagram iSiS program of a Proteus Labcenter

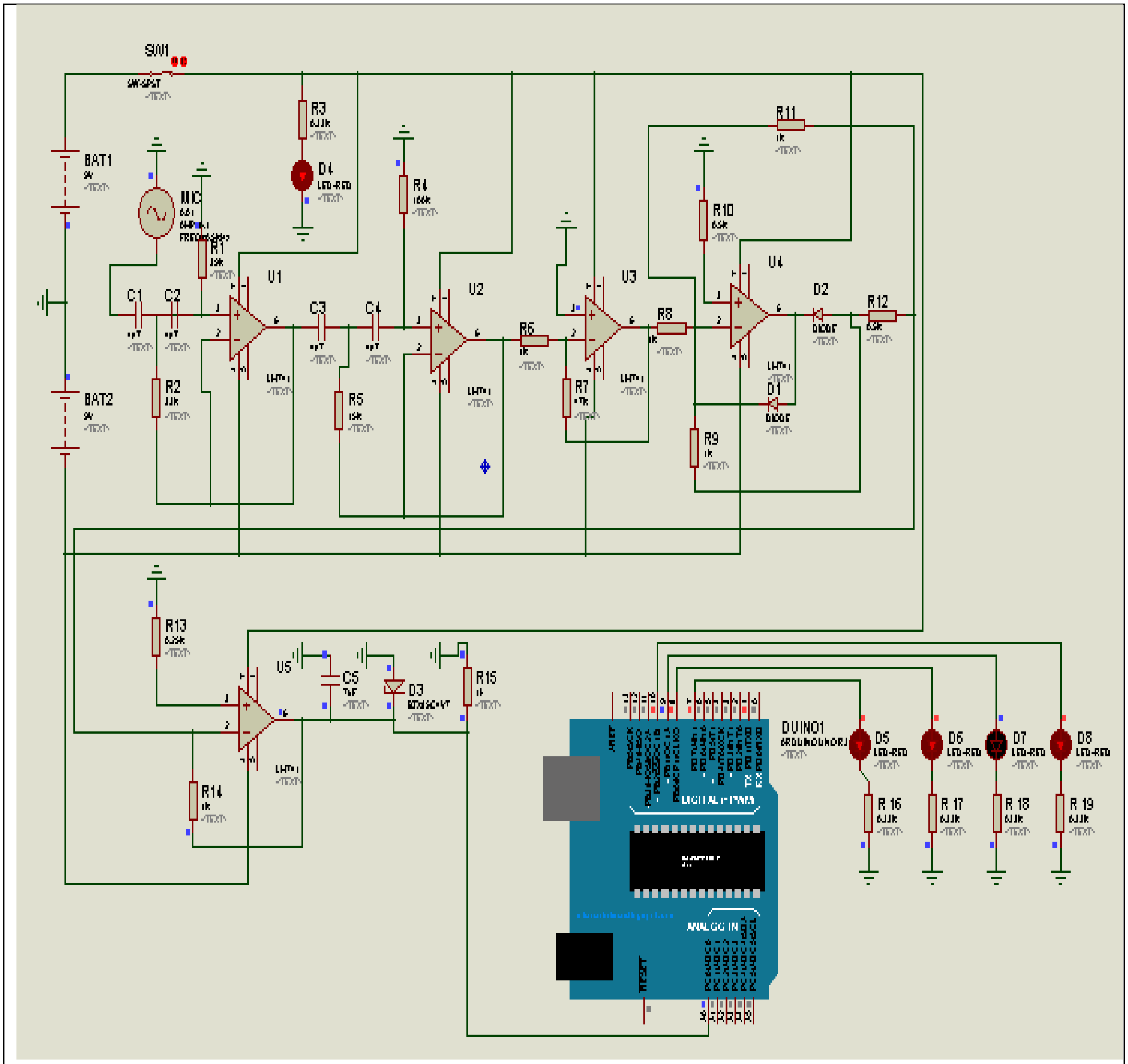


Figure 41: Simulation of a signal conditioning circuit and Arduino Microcontroller.

At this stage, the Arduino processing program to detect insect's pulse signal was moved into the theoretical Arduino board in the Proteus software. The circuit was tested before making the PCB circuit to see whether it was performing as the physical circuit that was tested on the breadboard.

(a) PCB design in IRES, Proteus software

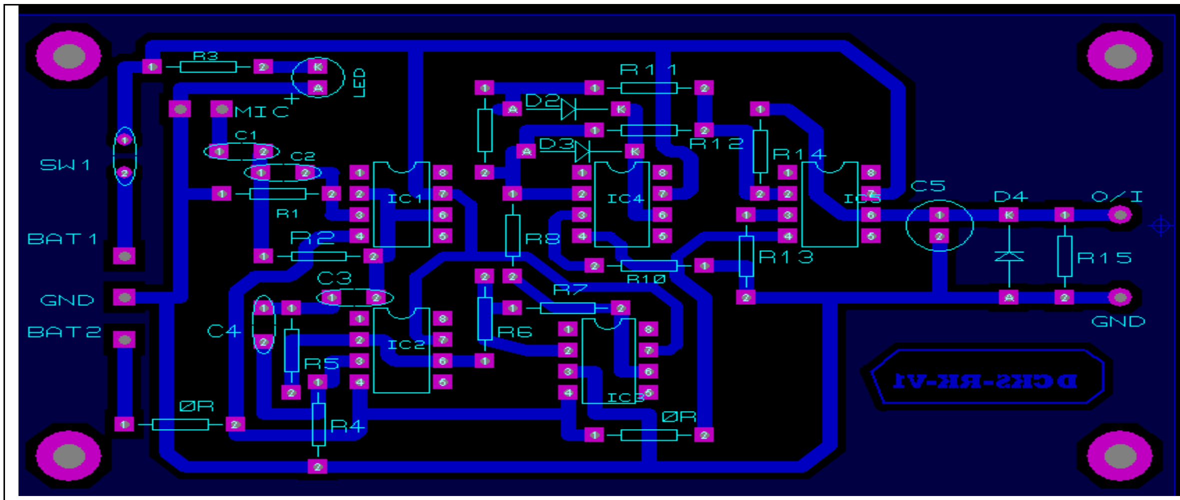


Figure 42: PCB board drawing. Ready for further fabrication processes

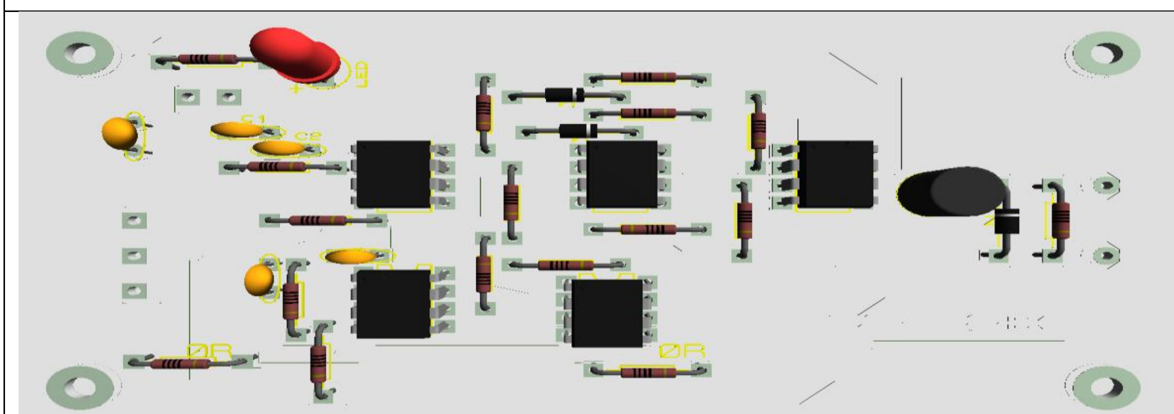


Figure 43: Top view layout of a PCB circuit, 3D view.

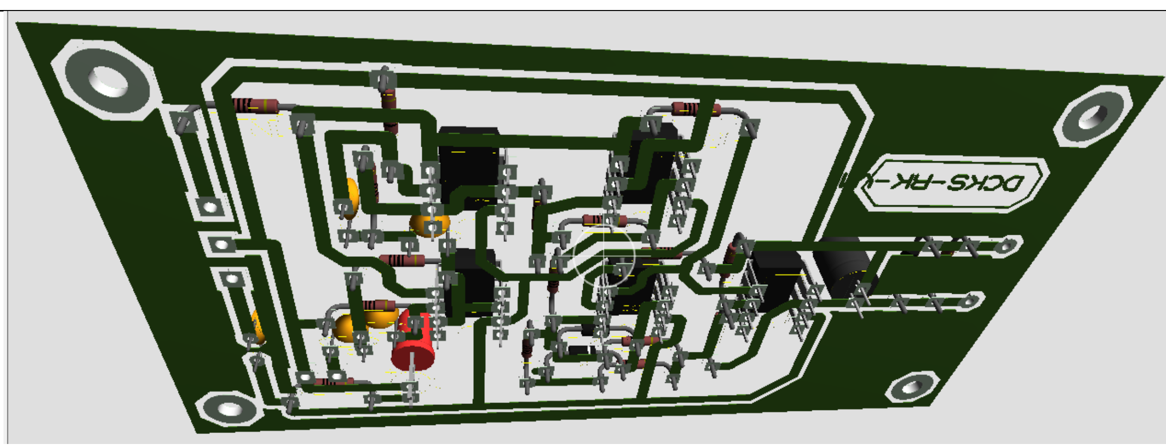


Figure 44: Bottom View layout of a PCB circuit. 3D view

3.2.5 Prototype bill of material and cost

Table 1: Prototype bill of materials

S/N	Item	Specifications	Qty	Unit	Unit Price ($)	Total cost ($)
1	Resistors	1 ohm - 10M ohm 1/4W Metal Film Resistors Assortment Kit	20	Ohm	0.001	0.02
2	Ceramic Capacitors	HIGH VOLTAGE CERAMIC DISC CAPACITOR 3KV 3000V 472 4.7NF 4700PF	5	4.7nF	0.28	1.40
3	Electrolytic Capacitor	10 x 17mm aluminum electrolytic capacitors 10uf 25v	1	7nF	0.16	0.16
4	Amplifier	UA741CN DIP-8 UA741 LM741 ST OPERATIONAL AMPLIFIERS IC	5	LM 741CN	0.24	1.20
5	Diode	1A 1000V 1N4007 IN4007 DO-41 Rectifier Diode Module High Quality	2	1N4007	0.02	0.04
7	Zener diode	1/2w 0.5W 5.1V Zener Diode 5.1Volt	1	5V	0.03	0.03
8	Battery	GP Greencell PP3 6F22 6LR61 MN1604 9V Block Heavy Duty Cell Battery	2	9V	2.25	4.50
9	Supper High gain Microphone	Only 0.23" L x 0.70" W x 0.31" H,20-160000Hz, 6-12V 20mA power, S/N Ratio more than 58dB	1	16000kHz	6.00	6.00
10	Toggle switch	Small Miniature Toggle KNX1*2 Circuitry Trait Rocker Switch 6mm Hole	1		0.76	0.76
11	Arduino Uno	STARTER PACK ARDUINO W/UNO R3	1		30.00	30.00
12	LED	New LED Round Red Yellow Green Light-emitting diode Mix Color 3mm 5mm	7		0.02	0.13
13	Copper clad	Copper Clad Laminate Circuit Boards FR2 PCB Single Side 20cmx30cm 200mmx300mm	1		5.31	5.31
14		PCB (estimate)	1		6.00	6.00
	Total					**$54.79**

3.3 Specific objective: testing the performance of acoustic based systems in detecting the pest infestations of stored maize

3.3.1 Instrumentation layout and testing

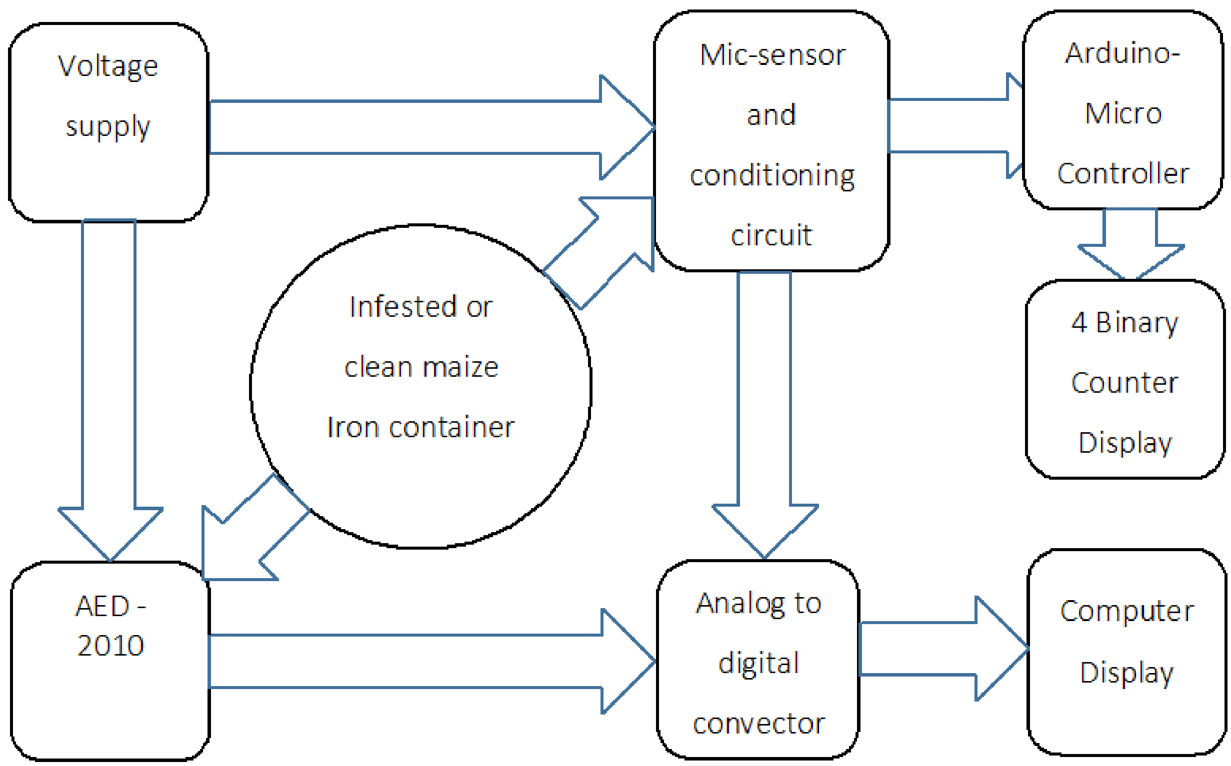


Figure 45: Instrumentation layout for testing the correct detection efficiency of a prototype device

The first step was to test the new device alone while having the microphone sensor and a signal conditioning circuit only. At this stage, the microcontroller was not involved. This connection also included the voltage supply (12V), analog to digital convertor (Virtual instrumentation for windows, Parallel ports, 12V DC, 500mA, UK model), and the computer with a Pico-oscilloscope display software as the external instruments. During this test, the Super High Gain microphone sensor (0.23" L x 0.70" W x 0.31" H, 20-160000Hz frequency response, S/N Ratio more than 58dB, 6-12V, 20mA power, Impedance 150 and ohms at 100Hz) was inserted into a 3kg maize container of either clean or infected maize. The sound signal collected from the maize container were then sent to the Analog to digital converter (ADC) for signal sampling. The signals from the ADC were sent into a computer with the Pico-scope display software. It was observed on whether the device showed signal differences between the clean and the infested maize when collecting records of 2442 voltage samples in 1 second.

The second test involved the Microcontroller and a four binary counter display. During this test, the signal from the Sensor and its signal conditioning circuit was shown in three displays: microprocessor Serial monitor, 4 binary counter display and the computer oscilloscope. The computer oscilloscope data was used as a reference on checking whether or not the displayed information in Arduino's serial monitor and a 4 binary counter were well-corrected with the insect signals and the written program.

3.3.2 Performance reliability tests

The prototype and standard device were used to collect sound signals in either clean or infested maize container concurrently. The amplifier circuit for the prototype device was set at a gain of 50 while the gain for the AED 2010 device was set at highest level. Also, the filter option for AED 2010 was off to allow the collection of the audible frequency range. The computer oscilloscope was set to collect 2442 samples per second. About 87 adults and 32 hidden larvae were put into the plastic pouch. The container to be tested had 3kg of maize. The Super High Gain microphone audio system from the new device system and the waveguide sensor (Model SP-1L, Acoustic Emission Consulting (AEC) Inc, Sacramental California, USA) of an Acoustic insect device system (AED 2010) were then inserted together into a clean or infested container of 3kg maize. The inlets of the container were covered with noise insulation rubber materials to reduce noise during the test.

3.3.3 Differentiating the noise signal from the infestation activity using the Prototype

The first analysis was done on the sound signals collected in the clean maize container. The purpose was to understand the noise background as well to establish the amplitude reference level for which both devices had no activity in clean maize. Since the experiment was conducted in the controlled laboratory environment, the signals with amplitudes in the infested maize which were greater than the amplitude reference level in the clean maize was considered as the *S. zeamais* activity. After establishing the reference amplitude voltages (0.2V) in clean maize for the new device, the comparison was done by looking at the counts for peak signals with the amplitude greater than the threshold of 0.2V in the infected maize. The other criterion was to look at maximum amplitude voltage for each collected sample.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Investigated acoustic behavior of internally feeding *Sitophilus zeamais* (*Coleoptera: Curculionidae*) in Stored Maize (Using standard device).

4.1.1 Clean and infested signal differences with AED 2010 acoustic instrument

There were large differences between the output signals from the infested and uninfected maize when looking at the Pico-oscilloscope display at the of 5-V amplitude scale. There was no peak signal output showing the activity greater than 1V in the clean maize while the infested maize had multiple signals with the amplitude between 0 and 5V as shown in (figures 25a and 25b)

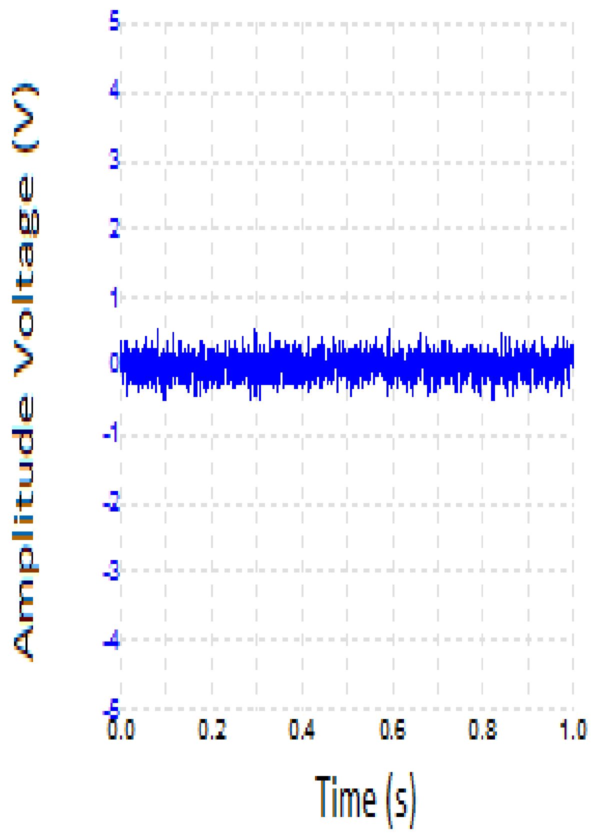


Figure 46 :Clean signal (uninfected maize)

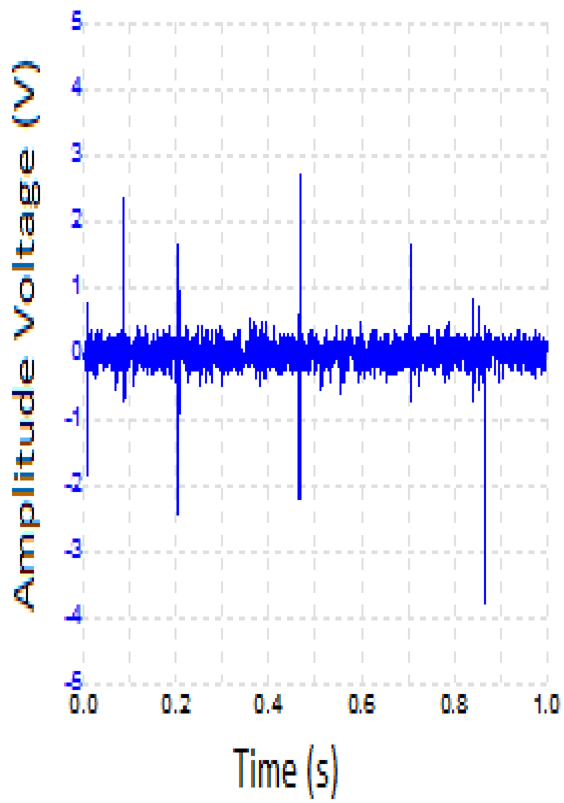


Figure 47: Infested signal (infested maize)

4.1.2 Occurrence of peaks and their magnitudes (using AED 2010)

The insect activity during morning, afternoon and night were different for the infested maize. This was established by counting the pulse voltages with amplitude greater than 0.7V which was the upper limit of signal amplitude in clean grain. There were few pulse counts per second during the afternoon compared to morning and night activities. The average counts for morning pulse was high (60) followed by night pulse (31) and lastly the afternoon pulse counts (2) as shown in Figure 26. There also were significant difference between the average activities for morning, afternoon and night periods (p-value < 0.01) possibly because of the adults in the sample. Further investigation is required to explain the differences in insect activity during morning, afternoon or night. It is speculated that these differences exist due to the diurnal temperature variations in a day (with cool mornings, hot afternoons and cool nights).

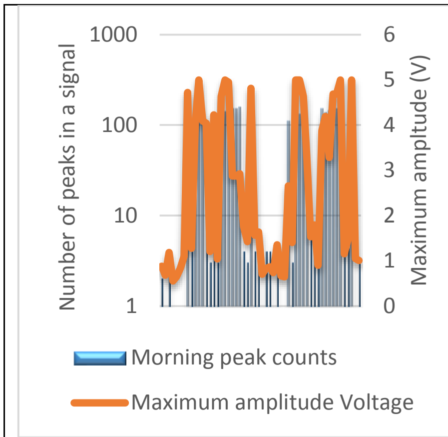


Figure 48: Insect's activity during morning

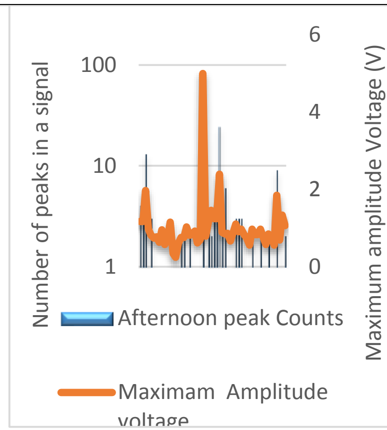


Figure 49: Insect's activity during afternoon

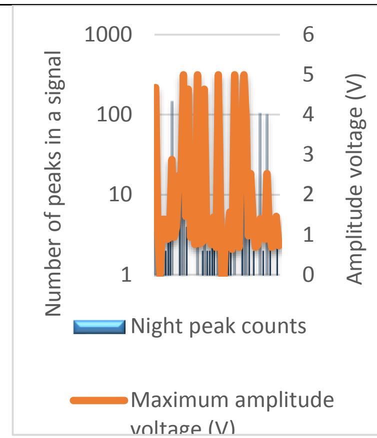


Figure 50: Insect's activity during night

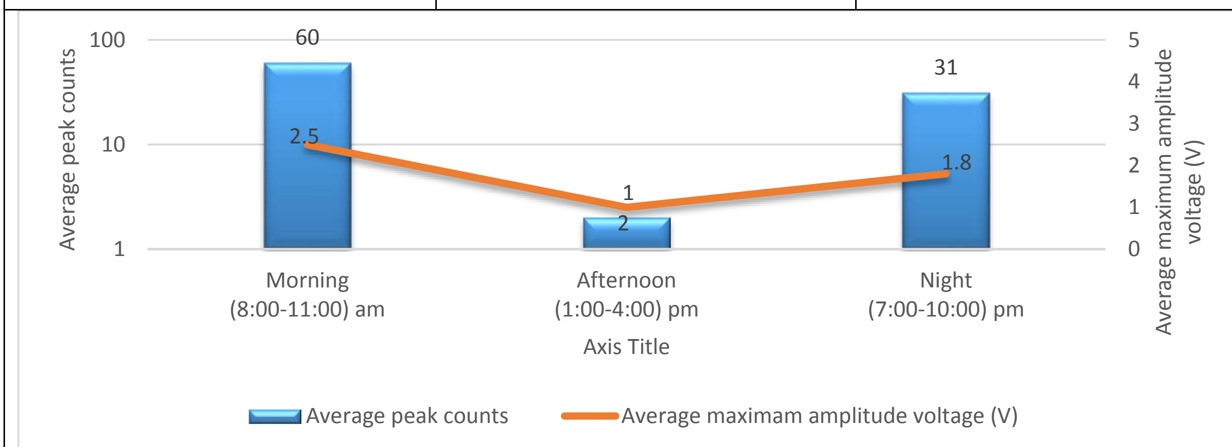


Figure 51: S. zeamais' morning, afternoon and night average activities in terms of peak counts for signals with amplitude greater than 0.7V and their corresponding maximum amplitude voltage

The average maximum amplitude was 2.5V for the morning data, 1.8V for the nighttime data, and lastly 1.0V for the afternoon data. Looking at Figure 48 to 51 (previously mentioned) on average activities between morning, afternoon, and night, the average number of peaks was directly proportional to the average maximum amplitude in a signal. More descriptive statistic summary details on both peak counts and amplitude voltage are included on Table 2 and Table 3.

Table 2: Descriptive statistic summary on average pulse counts of voltage peaks detected by standard device

Descriptive statistics	*Morning peak counts*	*Afternoon peak Counts*	*Night peak counts*
Mean	59.98	2.35	30.57
Standard Error	9.32	0.52	7.26
Median	6.00	1.00	3.00
Mode	3.00	1.00	0.00
Standard Deviation	68.46	3.83	53.33
Range	175.00	24.00	154.00
Minimum	0.00	0.00	0.00
Maximum	175.00	24.00	154.00
Confidence Level (95.0%)	18.69	1.04	14.56
Count	54.00	54.00	54.00

Table 3: Descriptive statistics summary on maximum amplitudes (V) detected by standard device at different monitoring sessions

Descriptive statistics	*Morning*	*Afternoon*	*Night*
Mean	2.54	1.00	1.78
Standard Error	0.23	0.09	0.21
Median	1.70	0.84	1.19
Mode	5.00	0.97	1.19
Standard Deviation	1.68	0.67	1.52
Range	4.44	4.76	6.01
Minimum	0.56	0.24	-1.01
Maximum	5.00	5.00	5.00
Confidence Level (95.0%)	0.46	0.18	0.41
Count	54.00	54.00	54.00

Descriptive Summary statistics on maximum peak signal at different monitoring sessions

4.1.3 Estimation of *S. zeamais* peak frequency during infestation

Considering the peak frequency in both clean and infected maize containers when the insects had greater activity (morning and night), there was a great difference in peak frequency (frequency showing the higher amplitude) in the signal range between 1 to 15 kHz. The infested container had the peak frequency mostly peaking at 7 kHz for the observed records compared to the signal in the clean maize container that had no such peaking frequency. The infested peak frequencies had the power gain ($20 \log V_{out}/V_{in}$) between -20 and -10dB. More examples of individual records that indicated this behavior are found in appendix 5.1. In addition there was a possibility of collecting the insect's signal at ultrasonic frequency. This possibility was observed by looking the LED on the AED-2010 after setting it to collect signals above 25 kHz. The rate of flashing LED was very negligible and the ultrasonic wave forms for clean maize and infested maize could not be differentiated.

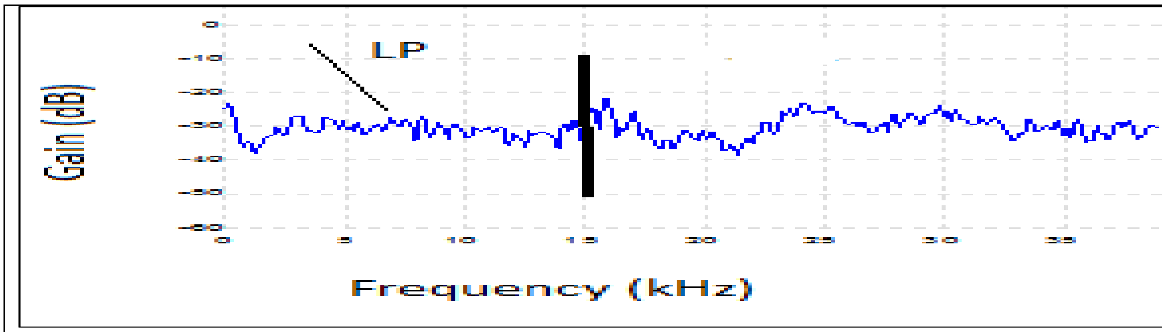


Figure 52: Example of individual record indicating the peak frequency in clean maize

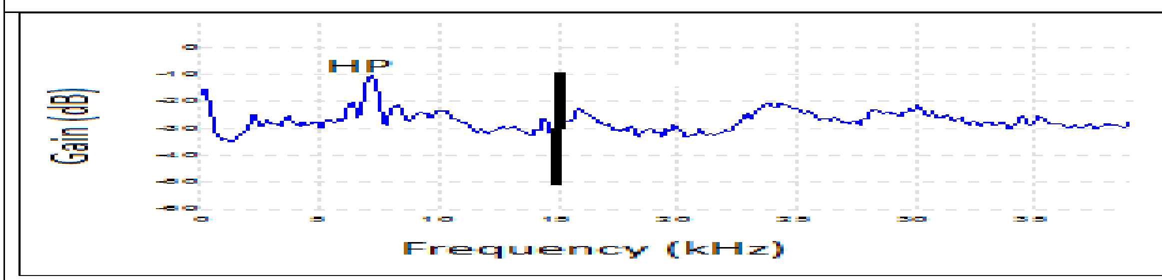


Figure 53: Example of the individual record on peak frequency in infected maize during Morning time

Figure. 52 to 53: Peak frequency in the waveform made by *S. zeamais* during the infection at morning and night in stored corn. LP: Low peak, HP: High Peak

4.1.4 Differences between signals detected by prototype in infested and clean maize. Clean and infested signal differences with the prototype

The prototype device was able to detect the presence of insects in the maize samples. All signals from the clean maize were lower than 0.2V in amplitude. The signals from the infected maize were greater than 0.2V but mostly not greater than 1V. Hence, the signals with the amplitude greater than 0.2V were categorized as S. *zeamais* sounds.

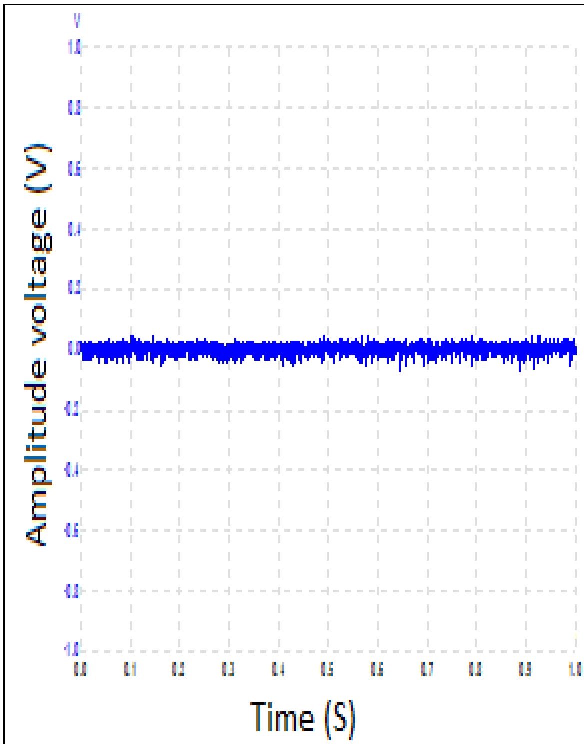


Figure 54: Signal collected by a prototype in a clean maize

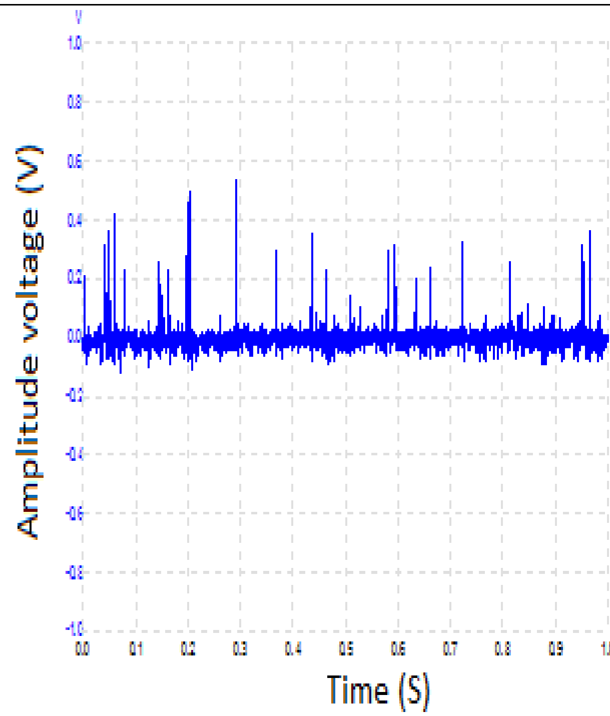


Figure 55: Signal collected by a prototype in infested maize.

4.1.5 Prototype performance on false negative and false positive tests.

The performance of the prototype device was explored by looking the false-positives and false-negatives. During the False-negatives test, the microphone was inserted in to the infested maize container to observe the possibility of the device to indicate "No Pests" while there are pests in the maize container. The case that the device indicated "No pests" was marked as zero while the one it indicated the presence of pests being marked as 1. Since the microphone was in the infected maize container, the device indicated the presence of pests by 93.3% (28 trials) compared to when it indicated no insects 6.7% (2 trials) as appears in Fig.56.

In addition, the prototype was also tested on the "False positives" detection. This was tested through inserting the microphone in uninfected maize container. The purpose was to observe the possibility of the device to indicate wrong information by indicating the presence of pests while no pests in the maize container. It was found that 86.7% (26 trials) indicated the expected results (No pests in clean maize) while 13.3% (4 trials) the device was wrong (indicated the presence of pests while the maize were clean) as shown in Fig57.

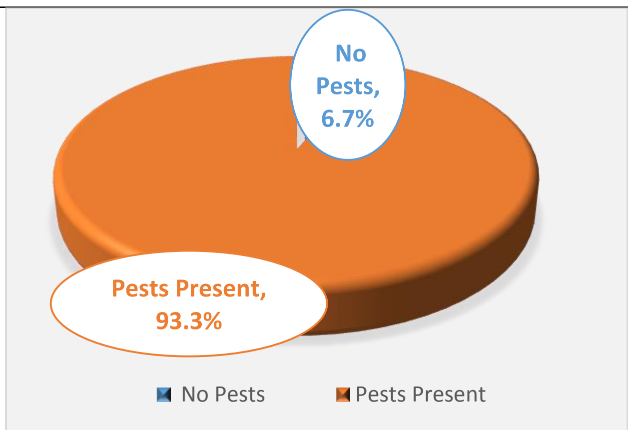


Figure 56: False negative visual inspection, microphone sensor inserted into infected maize container

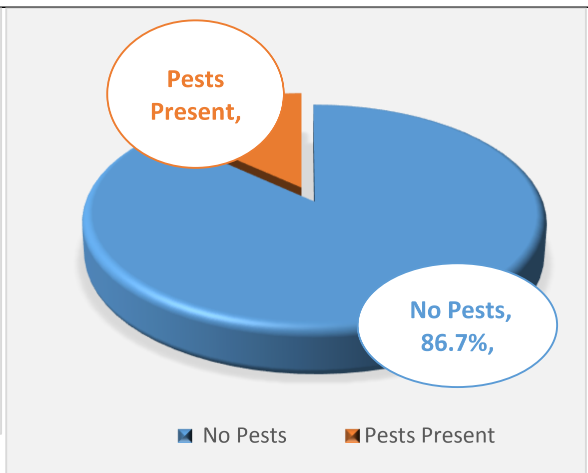


Figure 57: False Positive visual inspection, microphone sensor inserted into clean maize

4.1.6 Comparison between the prototype and the standard device

It was difficult to directly relate the detection capabilities of the standard and the prototype because of the differences in wave forms, system noise voltages (Fig 58, 59b and 60c) and their corresponding amplification. For example, because of differences in levels of background noise detected, the prototype detected insect signals at levels below the threshold of a system noise in the standard device. The prototype had a threshold of 0.2-V and the standard device had the threshold of 0.7-V. Therefore, we compared the number of amplitudes voltage greater than 0.7-V. By assessing at least the average pulse-counts for pulses with respect to their thresholds, the prototype had 18 counts/sec and the standard device had 21 counts/sec.

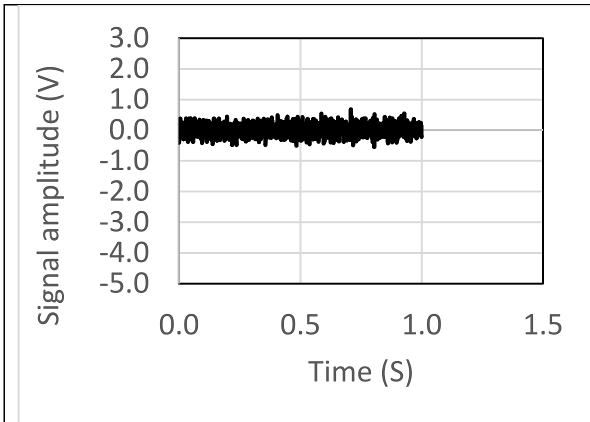


Figure 58: Background noise of a standard device in clean maize, threshold 0.7-V

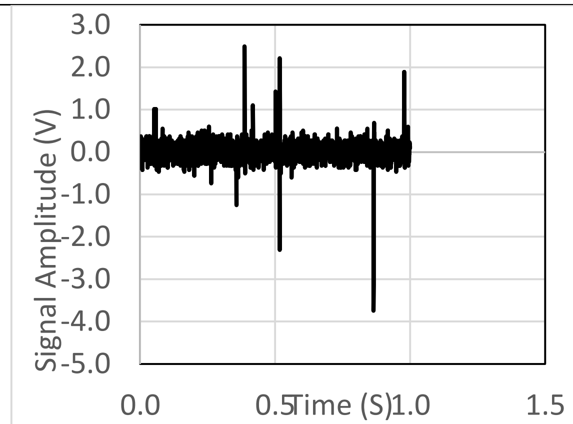


Figure 59: Infestation noise of a standard device in infested maize, amplitude between

0.7-V and 5-V

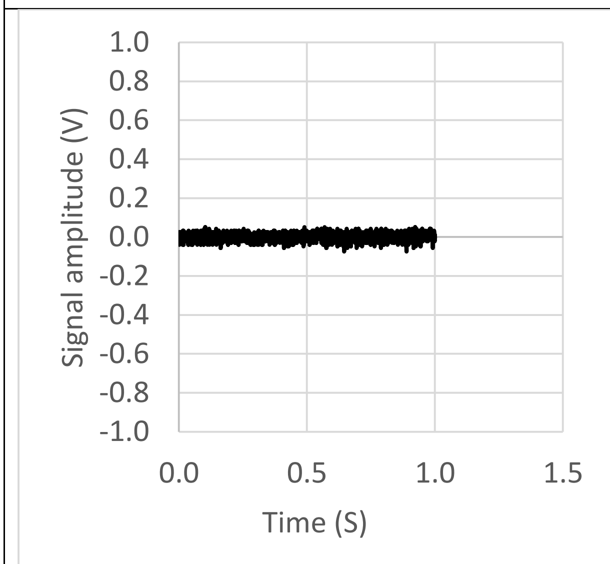


Figure 60: Background noise of a prototype in clean maize, threshold 0.2-V

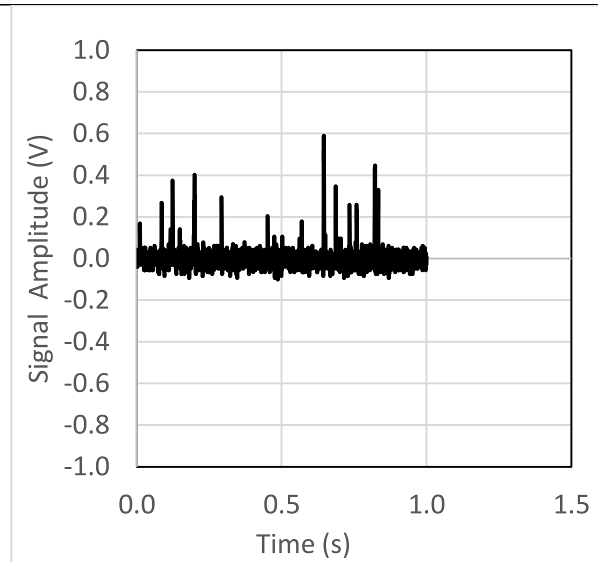


Figure 61: Infestation noise of a prototype in infested maize, amplitude between 0.2V and 1V

4.1.7 Number of peaks detected per second by prototype

The highest sample number of peaks collected in all sample was 42 while the least was 6 peaks in one second. The rate can vary depending on the number of insects and the location of insects from the sensor, and the rates of sounds produced by an insect at different times.

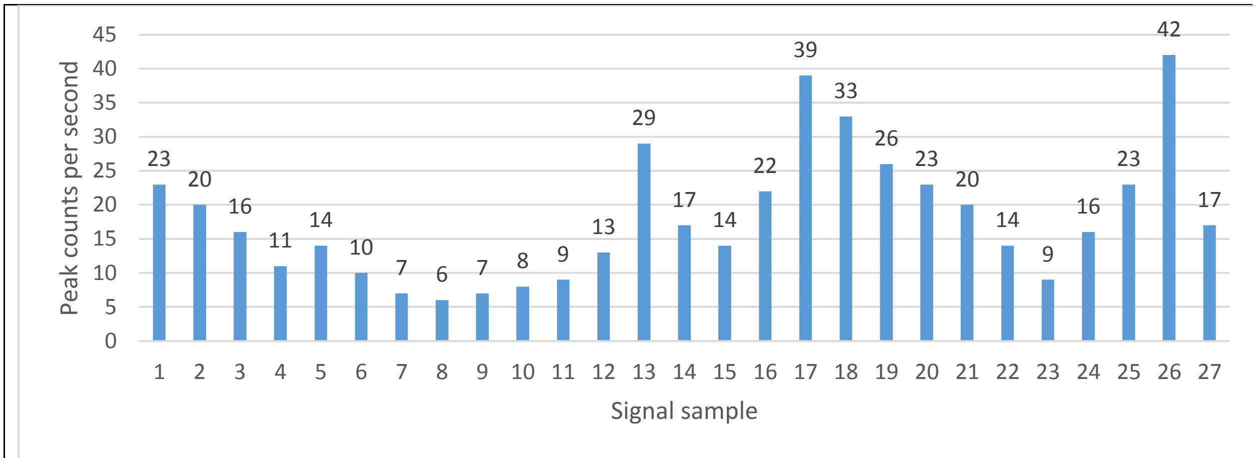


Figure 62: Response of number of peak with amplitude voltage greater than 0.2-V in in records collected by prototype from sample at different times

4.1.8 Maximum amplitude level detected by prototype in each record

The maximum amplitudes detected by the prototype ranged between 0.4 to 0.8V. Therefore, using the Arduino microcontroller may help to receive and process any voltage ranging from the threshold voltage (0.2V) to the maximum voltage of 1V.

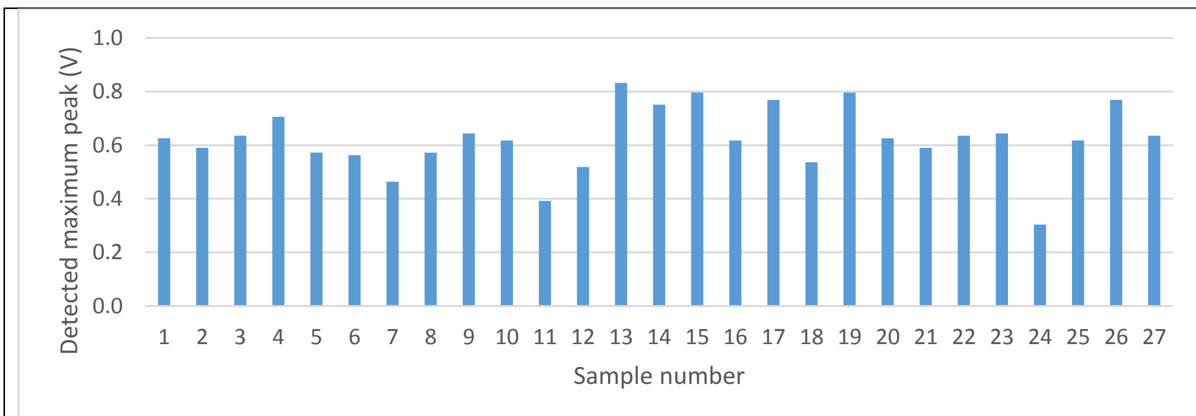


Figure 63: Maximum peak amplitude collected by prototype in each record

Table 4: Descriptive Statistics Summary on performance of a new device

Descriptive statistic	**Count for amplitude voltage greater than >0.2V**	**Maximum Amplitude**
Mean	18.0	0.62
Standard Error	1.84	0.02
Median	16.00	0.63
Mode	23.00	0.64
Standard Deviation	9.55	0.12
Range	36.00	0.53
Minimum	6.00	0.30
Maximum	42.00	0.83
Count	27.00	27.00
Confidence Level (95.0%)	3.78	0.05

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

In this investigation of acoustic behavior of internally feeding *Sitophilus zeamais* (Coleoptera: Curculionidae) in stored maize, signals from *S. zeamais* activity ranged between 1 and 15 kHz. The frequency of maximum power is near 7 kHz, similar to the sound spectra analysis on *S. oryzae* in cracked maize (Kiobia at el., 2015). These frequencies were peaking at the sound intensity (20 log V_{out}/V_{in}) between -20 and -10dB when the sound sensor is around 5-cm from the insect bag and operating between 84 and 90dB. Though there was a possibility of collecting the insect's signal in the ultrasonic frequency range above 25 kHz, the rate at which the signal with the amplitude above the threshold appeared was very low. The clean and infested wave forms at ultrasonic frequency range could not be differentiated.

By assessing the insect's activity behavior inside the grain in terms of amplitude level and number of amplitudes (signal peak counts per seconds), the afternoon activity was low compared to morning and night activities. Probably the insects may have the behavior of eating during mornings and nights, resting during afternoons. This could be due to insect's sensitivity to temperature changes during day and night. In addition to changes in the insect's activity during a day, the number of peaks/second and their corresponding amplitude level may also depend on the detection sensitivity of the acoustic instrument in use. In general, the literature about the insect's activity about morning, afternoon and night were limited.

From the second specific objective, to design and develop an acoustic based device that can detect the insect's infestation in stored maize, the high-pass Butterworth filter with the attenuation of frequency below 1 kHz was able to reduce the noise system to 0.2V when using a microphone system. Perhaps housing and fixing the microphone during the test may reduce more system noise. The design had high amplification for the frequency from 1 and 20 kHz. This was found to be very useful as the study of *S. zeamais*' behavior indicated the possibility of detecting its sound frequency within the range of 1 to 15 kHz.

In addition, the possibility of amplifying *S. zeamais* signal may depend on the input impedance and the pre-amplification of a sensor type (microphone or ultrasonic probe) and the amplification of the signal conditioning device. In other words, the higher the pre-amplification of the sensor output, the lower the amplification by the signal conditioning circuits. The use of an electronic signal conditioning circuit with a reasonable amplification of 50 times and a simple microphones (Super High Gain microphone sensor (0.23" L x 0.70" W x 0.31" H, 20-160000Hz frequency response, S/N Ratio more than 58dB, 6-12V, 20mA power, Impedance 150 and ohms at 100Hz) coupled with the microcontroller had good performance at detecting the *S. zeamais* infestation in a 3kg of maize in a container. But in case of using the ultrasonic probe (Model SP-1L, Model AED-2010) the signal conditioning circuit had to be added another stage amplifier to amplify the input signal by 100 times. Hence, the microphone was the best option as it operated without need of more amplification stage.

The prototype is using Arduino UNO as the microcontroller and limits additional noises by manipulating the insect's sound signals and using a customized program. In addition, this was a good entry to initiate a design study that can investigate the possibility of using a microcontroller and wireless microphones sensors to monitor many small storage facilities at a time. These microcontroller can support the addition of wireless components such as digital communication standard device (ZibBee-802.15.4 or Xbee) to transmit data to a mobile phone (Navin et al., 2013). It might be very effective to use the microcontroller node such as Seeeduino Stalker Version 2.3, as this has the SD card option that can help to store the information on insect activity for some period of time.

Also, the use of a 4 binary system to display the processed signal from the Arduino microcontroller was one of the improvement on the acoustic based systems compared to the other ones which use a single LED. The insect's activity peaks had to stay in the memory lighting up the LEDs until 15 peaks are counted by a program in a microcontroller. Hence a prototype user can see the past insect's activity action even if the insect are silent at the moment the user sees the device.

The device was also portable and designed to use dry cells with supply voltage from 9 to 12V. However, supplying power to the prototype with the solar system may add more value. This may reduce the cost of operation and may be useful to famers in local villages.

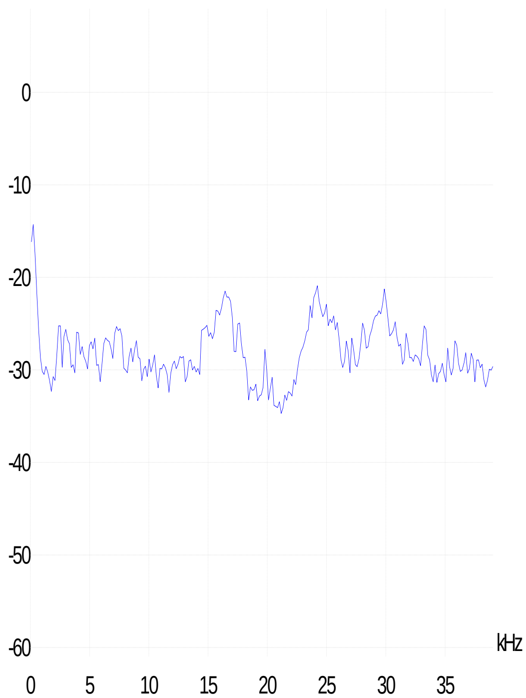
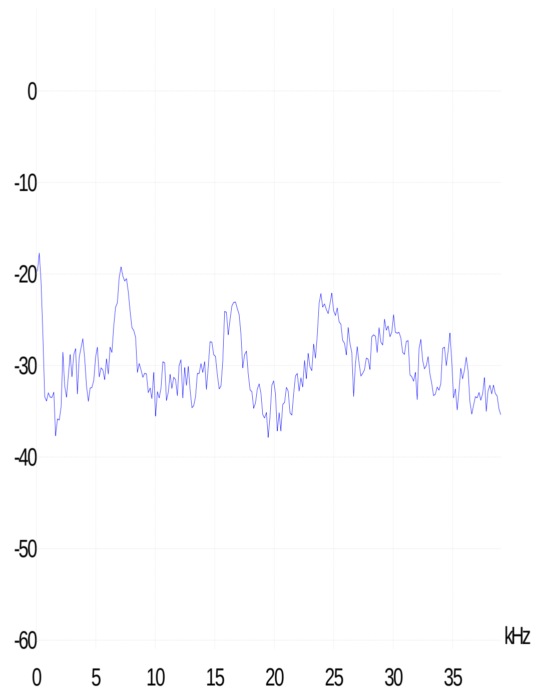
Furthermore, the design considered the prototype material cost as one of the important aspect. The material cost for a single device was nearly around $55 as shown in Table 1. The replacement of ultrasonic probe ($500) with a microphone ($6) reduced the prototype cost, significantly.

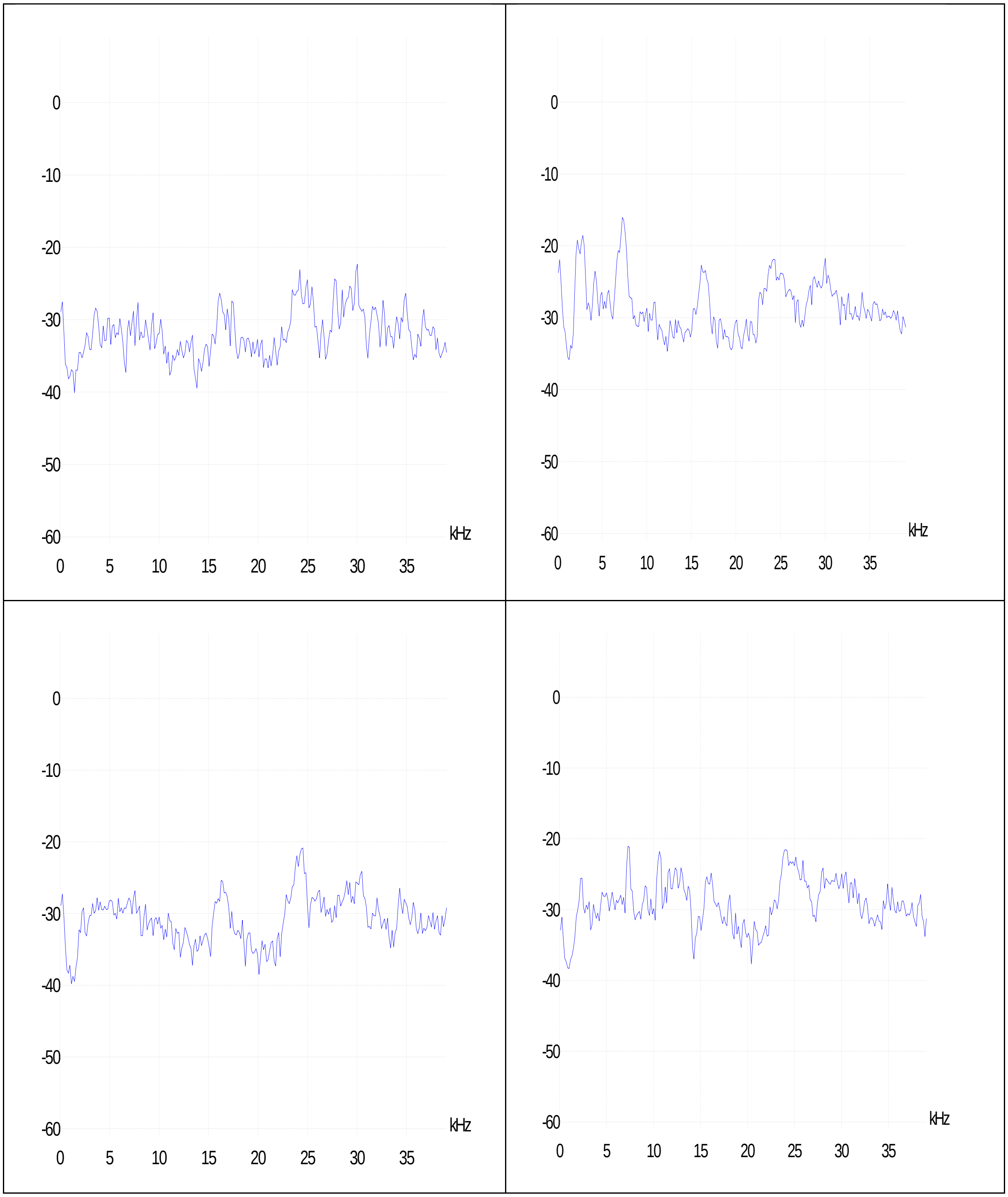
Lastly, from the study on the third specific objective; test on the performance of acoustic systems in detecting the pest infestations of stored maize. The prototype detected the difference between the clean and infected maize. The number of false positive was 13.3% and the number of false negative was 6.7%. By considering the signal difference, the prototype differentiated the clean and infected maize with a threshold of 0.2-V in a clean maize and amplitude level of 0.2V to 1V for infested maize. Because the amplitude level was higher in the infested maize compared to the amplitude obtained from clean one, then the designed prototype system was able to detect the pest infestation.

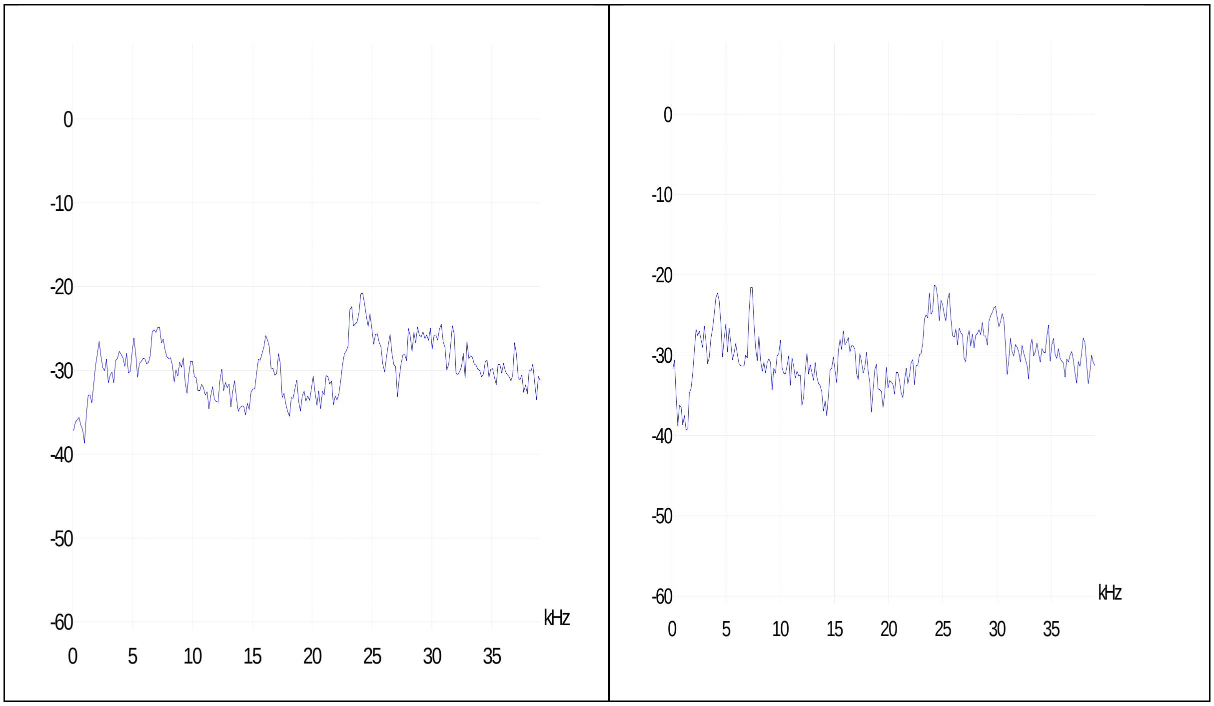
In general, there may be needed for future works in the following areas: First, there may be a need to house the microphone, add the display as well as using the multiple microphones instead of one microphone. Second, there is a need to collect sound data while including temperature and relative humidity in the grain storage facility. Third, insect's sound data should be collected for adults only or larvae only and have an approximation of age of insect be considered for acoustic characterization. Fourth, the study should be conducted to check the number of insects that can be heard in 1 kg of maize when using the prototype or AED -2010 system. The acoustic system performance should be tested on released insect's storage facilities such as bags of 100 kg or traditional *Kihenge* (about 500 kg) in Tanzania. This should also be done critically to identify particular signal features that can be used to distinguish *S. zeamais* sound from other pests and non–pest organisms in stored maize. Fifth, the prototype should be tested on other maize insect pests such as large grain borers (LGB). Sixth, further prototype tests should be performed on other grain insect pests that affects other stored grains. For example include weevils for beans (*Acanthoscelides obtectus*), rice weevils (Sitophilus oryzae) for rice, and peanut pests (Indian meal moth, red flour beetle, almond moth, lesser grain borer, and sawtoothed grain beetle).

Appendices

Appendix A: More examples on peak frequency found in individual recordings

<table>
<tr><td>Peak frequency in clean maize</td><td>Peak frequency in infested maize</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>


0
-10
-20
-30
-40
-50
-60
kHz
0 5 10 15 20 25 30 35


0
-10
-20
-30
-40
-50
-60
0 5 10 15 20 25 30 35
kHz
0
-10
-20
-30
-40
-50
-60
0 5 10 15 20 25 30 35
kHz

Appendix B: Arduino insect's sound processing program

```
int sensorPin = A0;    // select the input pin for the potentiometer
//int ledPin = 13;      // select the pin for the LED
int sensorValue = 0;  // variable to store the value coming from the sensor
Byte counter;
int ledPin[] = {7,8,9,10};
// the setup routine runs once when you press reset:
Void setup () {
  //counter=0;
  // initialize serial communication at 9600 bits per second:
  Serial. Begin (9600);
 // pin Mode (9, OUTPUT);
  Pin Mode (A0, INPUT);
  For (int i =0; i<4; i++)
  {
        Pin Mode (ledPin[i], OUTPUT);
  }
}
// the loop routine runs over and over again forever:
Void loop ()
{
  // read the input on analog pin 0:
  int sensorValue = analogRead(A0);
  // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V):
  Float voltage = sensorValue * (5.0 / 1023.0);
  // print out the value you read:
  If (voltage > 0.2 && voltage <1)
  {
    Counter = counter + 1;
```

```
    Serial.println (counter);
    Display Binary (counter);
    If (counter==15) {
        Counter=0;
    }
  }
  Else {
    Serial.println (0);
  }
  Delay (5);
}
Void display Binary (byte numToShow)
{
  For (int i =0; i<4; i++)
  {
    If (bitRead(numToShow, i)==1)
    {
      digitalWrite (ledPin[i], HIGH);
    }
    Else
    {
      digitalWrite(ledPin[i], LOW);
    }
  }

}
```

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