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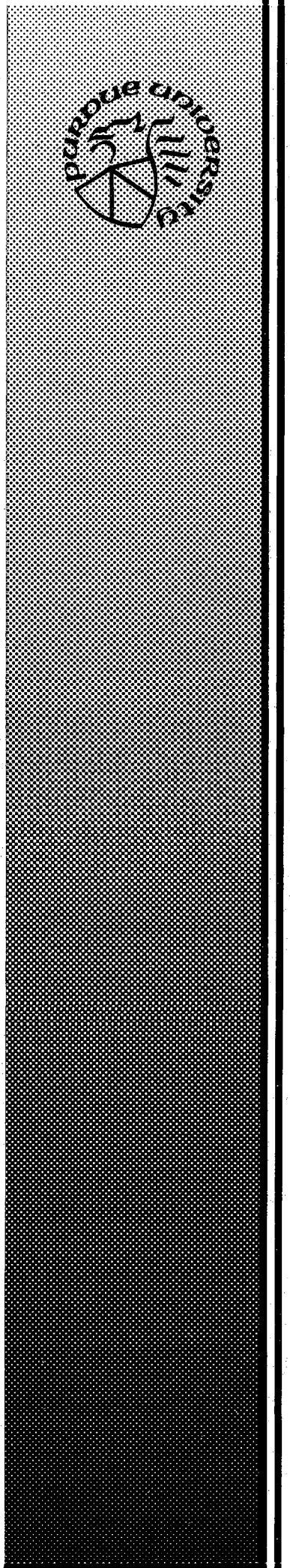

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This thesis is dedicated to my fiancee, Melissa Schwartz,
for standing by me in times of frustration.

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ABSTRACT

Klaassen, Richard E. MSEE, Purdue University. August 1989. Identification of Concealed Insect Infestations Using a Passive Ultrasound Monitor. Major Professor: Eric S. Furgason.

Concealed insect infestations in stored grain are responsible for large economic losses worldwide, and have traditionally been difficult to detect and quantify. A simple method of infestation detection and quantification has been developed, taking advantage of the ultrasonic emissions generated by the feeding activity of the insects. The acoustic signals generated by the insects are characterized as bursts of energy in the frequency range of 5 to 75 kHz, varying with the variety of seed being examined. These signals can be detected reliably by monitoring the seeds for sounds in a frequency band between 30 and 50 kHz. The stage of development of an insect, and thus the amount of damage of which the insect is capable, can be predicted by studying a time series of these signals. A basic signal acquisition procedure has been developed which amplifies the variations in the pattern of acoustic signals associated with different stages of larval development for the cowpea weevil. A histogram is constructed to describe the time intervals between successive feeding events, and is compared to typical histograms associated with each stage of development. In over 80% of the cases, an acquired histogram from a cowpea weevil at a known stage of development was most similar to the typical histogram associated with insects at the same stage of development. Using this correlation to quantify an infestation could lead to a significant reduction in the use of pesticides for insect eradication.

CHAPTER 1

INTRODUCTION

1.1 Motivation for this Research

Many species of insects derive their subsistence from dried plant material. When such material is gathered in large quantities in storage, insects also gather to gorge themselves and propagate their species on this cornucopia. In the United States, buyers, sellers, and users of such products lose nine percent of their crops to such pests annually, and losses are much higher in other parts of the world.

These losses could be reduced if the grain owners had a means of detecting and quantifying an infestation before it caused significant damage. Then pesticides could be applied at strategic times for optimum insect control. A solution for obtaining such information about infestations is to monitor the grain for ultrasonic emissions generated by the feeding activity of the insects. This research was initiated on the hypothesis that when an insect thrusts its mandibles into the rigid substrate of a kernel of grain, a burst of ultrasound is generated.

In addition to determining the presence of the insect, a careful analysis of the ultrasonic signal can yield much information about the insect. The number of events detected is expected to vary as a function of the number of insects present, since each insect feeds as an individual, with no regards to its neighbor. Variations in the signal may also correspond to changes in the anatomy and behavior of the insect as it ages and grows, or to morphological or genetic differences between different species of insects, depending on the structure of their mouth-parts and their feeding habits.

1.2 An Illustrative Pest: The Cowpea Weevil

One grain which is highly nutritious, can be grown worldwide, and is routinely infested is the cowpea, also called southernpea and blackeyed pea. The cowpea weevil, *Callosobruchus maculatus,* is the most significant pest of

cowpeas worldwide. An adult of this species is shown in the photo in Fig. 1. Although the infestation is initially insignificantly small in the field, it grows exponentially when the grain is stored. If these insects are not properly controlled, they are capable of causing extensive damage to the grain, as the example in Fig. 2 shows. Often, 30 percent of the grain weight is lost within six months, with up to 70 percent of the seeds being infested and virtually unfit for consumption [1]. In Nigeria alone, approximately fifty million dollars worth of food is lost to the cowpea weevil annually.

The life cycle of the cowpea weevil spans approximately one and one-half months, and consists of four larval instars, a pupal stage, and the adult stage. The insects cause all of the seed damage during the larval instars. Each of these larval instars lasts on the order of four days, and ends when the larva sheds its skin and develops new mouth-parts. Except for the steady increase in visceral mass during feeding, all of their anatomical development takes place abruptly during these molts. The size of the larva increases geometrically with the stage of larval development, as is demonstrated in Table 1. Similarly, the amount of damage caused by this insect is estimated to increase at a geometric rate [2]. Several insects at the stage when they inflict most of their damage, ones in the fourth larval instar, are shown in Fig. 3. Note that first instar cowpea weevil larvae are 0.3% the size of these insects.

Table 1. Growth of cowpea weevil larvae, demonstrated through increasing average weights at each stage of development, [3].

Stage of Development	Portion of Larval Lifespan. (Days) (Begins-Ends)	Average Wet Weight of Larvae (mg)
First Instar	0 - 2	0.03
Second Instar	3 - 5	1.12
Third Instar	6 - 8	4.40
Fourth Instar	9 - 13	9.71

Figure 1. An adult cowpea weevil resting on a cowpea.

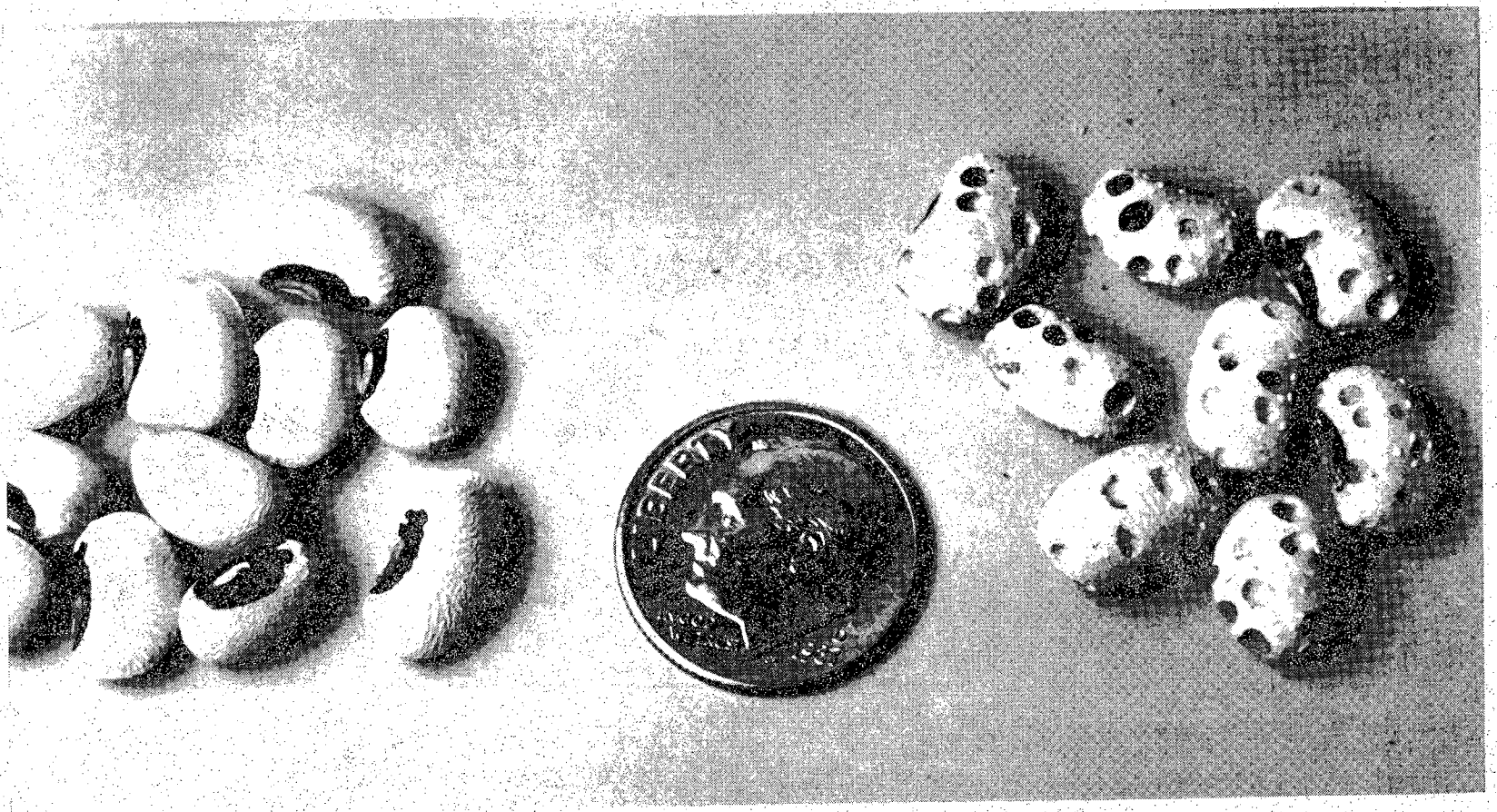


Figure 2. An example of the type of damage caused by cowpea weevils.

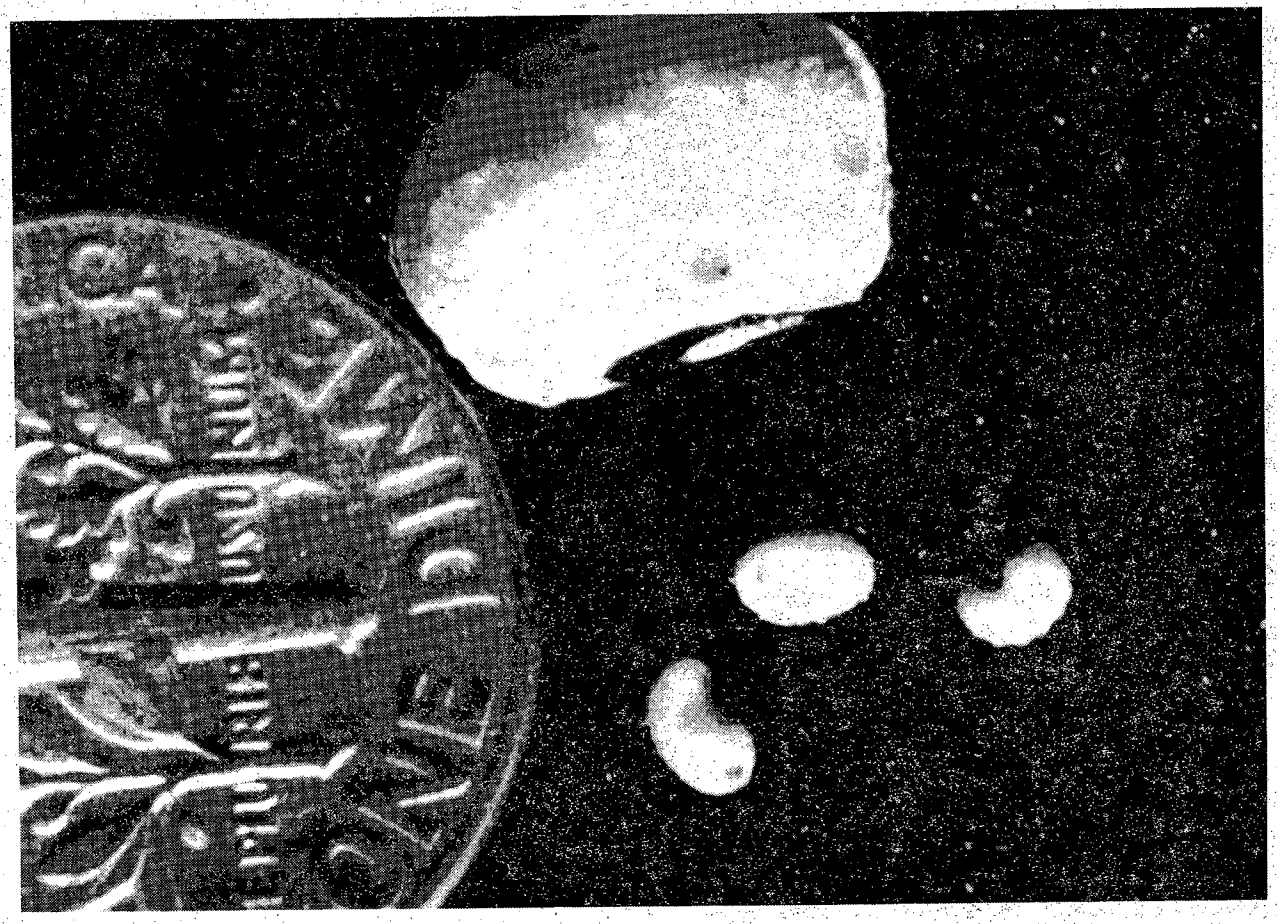


Figure 3. Three cowpea weevil larvae in their fourth instar; the stage of development when they cause most of their damage.

Typically, control of insect infestations is achieved by chemical fumigation. However, grain owners would prefer to avoid fumigation whenever possible because of environmental and economic concerns. Pesticide use could be significantly reduced and much money could be saved if fumigation was performed only when an infestation was at a stage which could create significant damage to the crop. For the example of the cowpea weevil, if one could detect an infestation, and determine that the insects were in their first or second larval instar, the grain could be fumigated immediately, and over 90% of the potential damage could be avoided. If the insects were already in their fourth instar, then most of the damage would have already occurred, and the grain could be used for its intended purpose before the next generation of insects hatched.

Traditionally, a cowpea weevil infestation has been difficult to detect and quantify because this insect spends most of its life hidden inside the bean. The conventional means of detection has been visual inspection; a person has to inspect individual seeds to find the small, white egg of the insect. One can only begin to imagine the difficulty of this task after viewing an infested seed such as the one in Fig. 4. Upon finding the egg, the inspector only knows that an insect may be present, to find out the stage of development of the insect, the seed must be cut open, and the larva must be found and closely examined. Locating this larva is also a difficult task because the larva may be no larger than the egg, and one is not sure what path the insect has traveled. Upon dissecting the seed for this purpose, the fragile-skinned larva is easily destroyed, making it impossible to determine the stage of larval development. This task becomes even more formidable for other insects, such as the closely related bean weevil, *Acanthoscelides obtectus*. The egg of this insect does not adhere to the infested seed, so locating the seed housing the larva is virtually impossible, and the stage of development of the insect can not be determined. A superior means of detecting these insects and determining their quantity and stage of development is needed.

1.3 Infesting the Substrate

Cowpeas and kidney beans were infested with two closely related species of insects, the cowpea weevil and the bean weevil, so that their acoustic emissions could be measured. To obtain a correlation between the acquired signals and the specifics of the infestation, the number of insects in each seed, as well as the species and stage of development of the insect needed to be known. The infested seeds were obtained by placing several adult insects in a container with

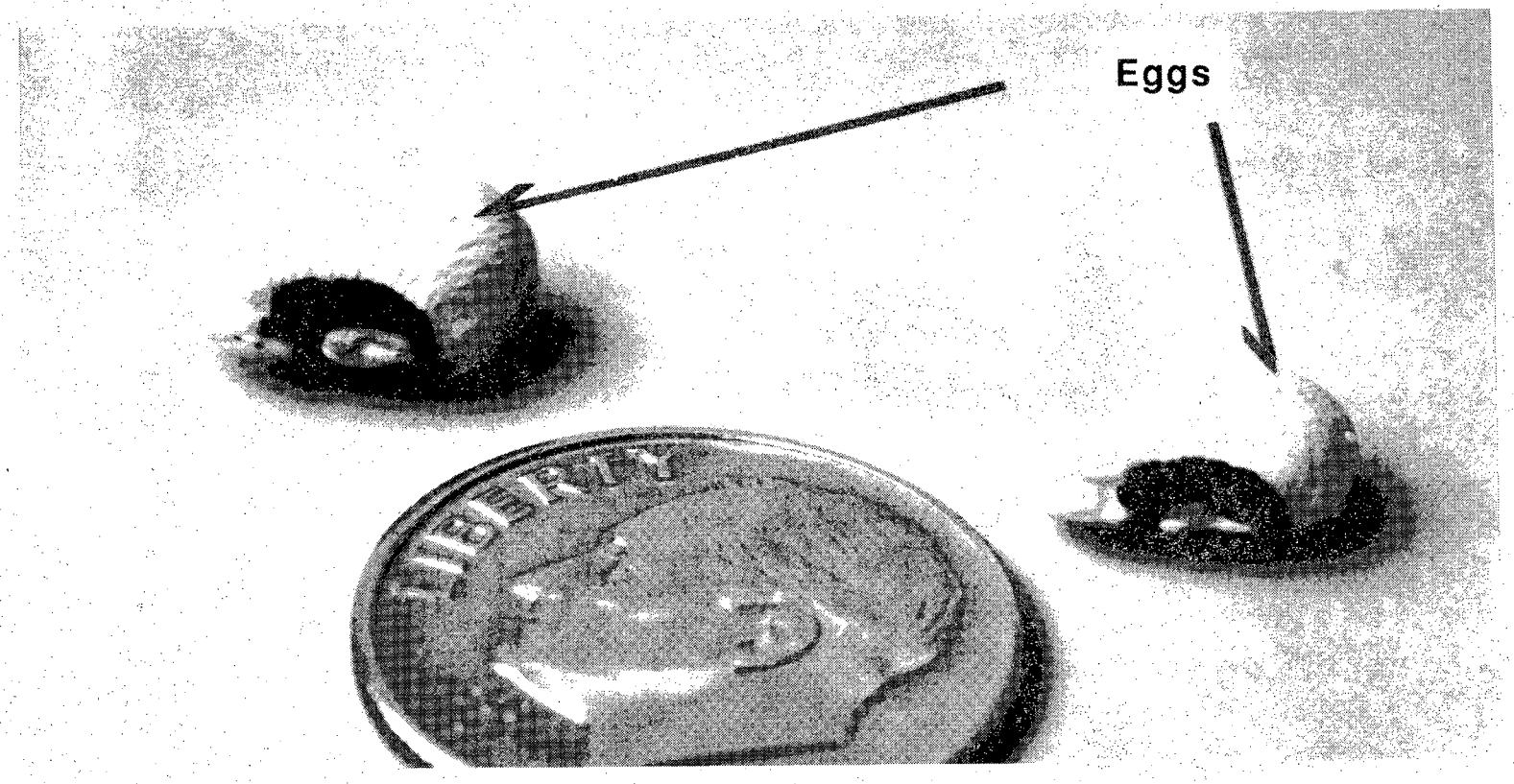


Figure 4. Cowpea weevil eggs on cowpeas.

uninfested seeds for one day, allowing them to lay eggs on the seeds. The cultures were separated by insect species, so only one species of insect could be present in each seed. By removing all but a specific number of eggs from each seed, the number of insects present inside each seed could be known exactly. By knowing the day on which the egg was laid, one could predict when the egg would hatch, and when the insect would be in each of its larval stages. The exact stage of development of the insect could be reliably determined by monitoring the sound emissions coming from an infested seed for a short period every day. Every time the insect molts, it is silent for approximately one day. Thus, by counting molts, one could determine the exact instar of the insect.

1.4 Types of Signals Expected from Insects

Based on what is known about beetles in general, one can make several predictions about the signals received from their feeding activity. These emissions could have several modes of generation. If the insect bites or fractures a particle from the seed, one might expect to hear an impulsive, crunch-like sound. If the insect scrapes at the seed, one might expect to hear a prolonged grating sound.

As the insect grows, the parameter expected to change the most would be the amount of signal energy generated by the insect. The size of the insect grows at an geometric rate with respect to its stage of development, as was seen in Table 1. To increase in size geometrically, one would expect the feeding to increase geometrically as well. This increase in feeding could be manifested two ways: as an increase in the number of bites taken out of the bean, or as an increase in the size of the bites. For the former case, the individual acoustic emissions would be expected to be unchanged throughout the lifespan of the larva, but more of them would be detected. For the latter case, the magnitude of the individual acoustic signals would be expected to increase, corresponding to the amount of material consumed in each bite.

As one begins to monitor the acoustic emissions generated by these insects, intuition about what changes to expect as the result of insect-related variables increases dramatically. Chapter four focuses on one such variable, insect age, and the resulting changes in the acoustic emissions. But first, chapters two and three deal with methods of receiving insect-generated signals; how to maximize the likelihood of detecting their emissions. Finally, the observation of the

progression of the signal characteristics can allow one to draw many conclusions about the general habits of the insect. A small sampling of these conclusions shall be discussed in chapter five, along with the general conclusions about this research.

CHAPTER 2

DETECTING THE INSECT SIGNAL

2.1 Calculating the Natural Frequencies of Beans

For an acoustic signal generated by an insect concealed within a seed, the frequency spectrum of the signal received at the outer surface of the seed is greatly influenced by the natural frequencies of the seed. Regardless of the spectrum of the original signal, the seed will strongly favor some frequency components over others. By identifying these natural resonances, and then monitoring the seeds for acoustic energy in these frequency bands, the chances of detecting pests within the seeds can be maximized, while minimizing the susceptibility of the system to noise.

Predicting the natural frequencies of a bean is no simple task. These frequencies are dependent on the velocity of sound in the bean, as well as the size and shape of the bean. Of these, the shape is the most difficult parameter to describe. Modeling the bean as a simple shape may make the size difficult to describe as well, because the chosen shape may be defined by dimensions which are not easily obtained from the actual shape of the bean. Generally speaking, however, the maximum length and width of a cowpea cotyledon are 11 mm and 5.5 mm respectively, and the thickness ranges from 1.5 to 2.5 mm across the length and width of the cotyledon.

2.1.1 Measuring the Physical Constants of Beans

The velocity of sound in a cowpea cotyledon was measured by placing a constant-thickness portion of cotyledon between two transducers, and measuring the amount of time required for a pulsed, 40 kHz acoustic signal to travel through the material. In making this measurement, a moderate amount of error was present. This error was associated mostly with the force of coupling between the cotyledon and the transducers, which was difficult to regulate. The measured values generally fell in a range of 200 to 400 m/s, with

a median value of approximately 250 m/s. This same procedure was applied to a kidney bean cotyledon, and the median velocity in this substrate was measured at 340 m/s.

These values of sound velocity are low compared to other rigid substances, but are certainly reasonable. This can be verified by examining the value of the modulus of elasticity and the density of the cotyledon. These parameters are related to the velocity of sound by the relationship described in Eq. 1, [4]:

$$E = c^2 \times \rho \tag{1}$$

In this equation, c represents the longitudinal sound velocity, ρ represents the density, and E represents the modulus of elasticity. Once the velocity and density are known, then the modulus of elasticity can be compared to that of similar materials.

The average densities of cowpea and kidney bean cotyledons were measured by calculating the ratio of mass to volume of a group of 40 cotyledons. The skin and eye of each seed were removed so that only the cotyledons remained, and then the mass of the group of cotyledons was measured while it was still dry. The volume was measured by immersing them in water and measuring the displaced volume. The densities measured for cowpeas and kidney beans were 1300 and 1335 kg/m^3 respectively. These values are subject to a moderate amount of error, depending on the humidity of the surrounding environment. This is the result of the seeds being hydrophilic, which causes the dimensions and mass of the seed to change as it absorbs moisture.

The modulus of elasticity indicates the hardness of a substance. Thus, by comparing the hardness of beans to other substances, while also comparing the values calculated for the modulus of elasticity, one can verify the velocity of sound. Equation one gives a resulting modulus of approximately 8.1×10^7 $kg/(m \cdot sec^2)$ for the cowpea and, 15.4×10^7 $kg/(m \cdot sec^2)$ for the kidney bean. These values are slightly higher than that for cork, [5], indicating that these cotyledons are harder than cork, and the values are slightly lower than that for dry spaghetti, [6], indicating that these cotyledons are softer than spaghetti. In addition, because the modulus is higher for kidney beans than cowpeas, kidney beans must be harder than cowpeas. Indeed, each of these indications seem to be correct. Thus, 250 m/s and 340 m/s are reasonable values for the speed of sound in cowpea and kidney bean cotyledons, respectively.

2.1.2 A Simple Model for the Bean

The bean has a rather complicated shape, one that is not easily analyzed in terms of sound propagation characteristics. The shape of a typical bean is shown in Fig. 5, where it can be seen that the shape could be described as two shells placed in contact with each other around the edges, leaving an air cavity in the center. Each shell is comprised mostly of a homogeneous cotyledon, the characteristics of which are expected to determine the natural frequencies of the bean.

Several models were considered as representations of a cotyledon. One possibility was to model it as a thin plate or shell, either curved or flat, square or circular, with the sound traveling as transverse waves or lamb waves. Although a bean cotyledon has the appearance of a curved plate or shell, the assumption that the plate is thin is inappropriate. Typically, for a plate to be thin, its depth should be on the order of one-tenth of its length and width, or less, [7]. The dimensions listed above indicate that these shells are too thick to be modeled as anything "thin".

Because a bean is somewhat rounded and hollow in the center, it could be modeled as a hollow sphere. However, because of the split between the two cotyledons, sound is reflected at the boundaries, and the bean does not exhibit the resonances expected from such a sphere, [7].

The most appropriate simple model for the cotyledon of a bean is a solid rectangular block. Then the simple model for a whole bean would be two solid blocks with simple supports at the edges. With this model, the natural frequencies of an isolated cotyledon can be predicted using Eq. 2, [8]:

$$f_{(n_x, n_y, n_z)} = \frac{c}{2}\left[\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2\right]^{1/2} \qquad (2)$$

Where (n_x, n_y, n_z) represents the mode number, and l_x, l_y, and l_z are the estimated length, width, and thickness of the cotyledon. The parameter c represents the velocity of sound in the cotyledon.

Although the model used to estimate the natural frequencies of the bean was rather simple, finding the solutions to Eq. 2 was not. The length, width and thickness were approximated to be 11 mm, 5.5 mm, and 2 mm respectively. These values were obtained by estimating the mean values for a typical cowpea, and measurements differing by as much as 0.5 mm might be found by others examining the same bean. An even greater difference could be expected for measurements on different beans, due to the differences in bean size.

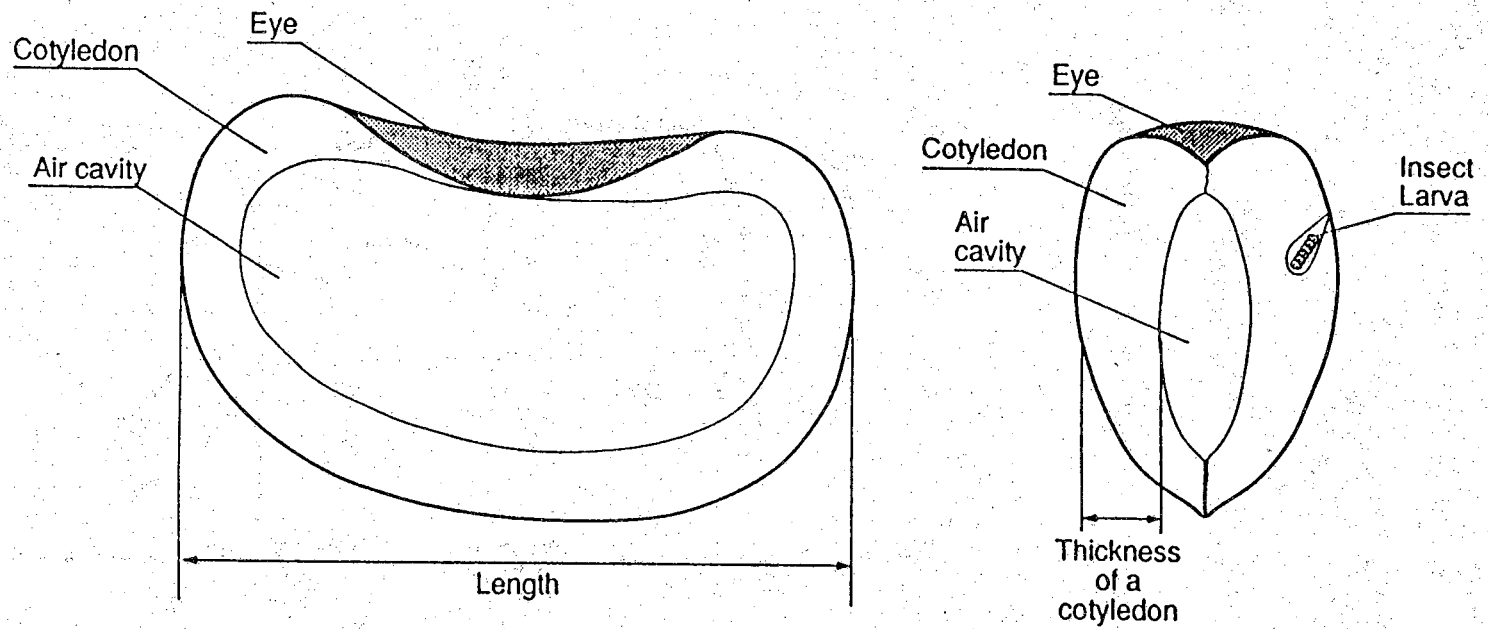


Figure 5. Cross sections of a typical bean.

The validity of Eq. 2 for predicting the resonances in a rectangular block of cotyledon was verified by measuring the natural frequencies of such a block. Cowpea cotyledons were carved into rectangular shapes of known dimensions so that the material under test would match the model as closely as possible, and the signal was supplied by a cowpea weevil residing within the bean. The signals were received using a Massa 40 kHz transducer, [9], (see Appendix A), and were examined to see which frequencies were favored by the block of cotyledon.

The transducer was not selective to the narrow band of frequencies at 40 kHz in this test, because the seed portions were placed on the face of the 40 kHz transducer, and the sound was directly coupled with the piezoelectric element. This point was demonstrated by placing brass and aluminum rods of known dimensions and physical properties against the face, which were excited by a broad band acoustic noise source, jingling keys. In this test, the natural frequencies of the rods were detected, and nothing was detected at 40kHz.

The resonances of the carved block of cotyledon material were measured and compared to the normal modes of vibration for a rectangular block. The natural resonances measured corresponded directly to the lowest order modes for a rectangular block with a sound velocity of 250 m/s, as shown in Fig. 6. The measured frequency for each mode present was within 8% of the predicted value. This is a relatively small error when one considers that the block was not exactly rectangular, and that the insect has created a small cavity inside the block, so that the block is not entirely solid.

In spite of the curved edges and varying thickness of a cotyledon, the natural frequencies calculated for a block of similar size and material constants agreed with the measured values for the cotyledon. An example of the frequencies recorded in a cotyledon and the corresponding predicted values can be seen in Fig. 7. The correlation between the predicted and measured values is fairly repeatable; the error is generally within 10%, and varies with the coupling force and transducer position on the seed. These results indicate that the received signals were the result of the resonance of sound waves traveling along the length and width of the cowpea. The lowest order mode for a half cowpea typically had a natural frequency of about 12-15 kHz, and higher order modes between 18 and 75 kHz.

Whole cowpeas exhibited a lowest order frequency of about two-thirds that of a half cowpea, as demonstrated in Fig. 8. This is most likely the result of the coupling between the halves. They are not coupled well enough for the seed to react to a sound source as a spheroid, but they are coupled well enough for

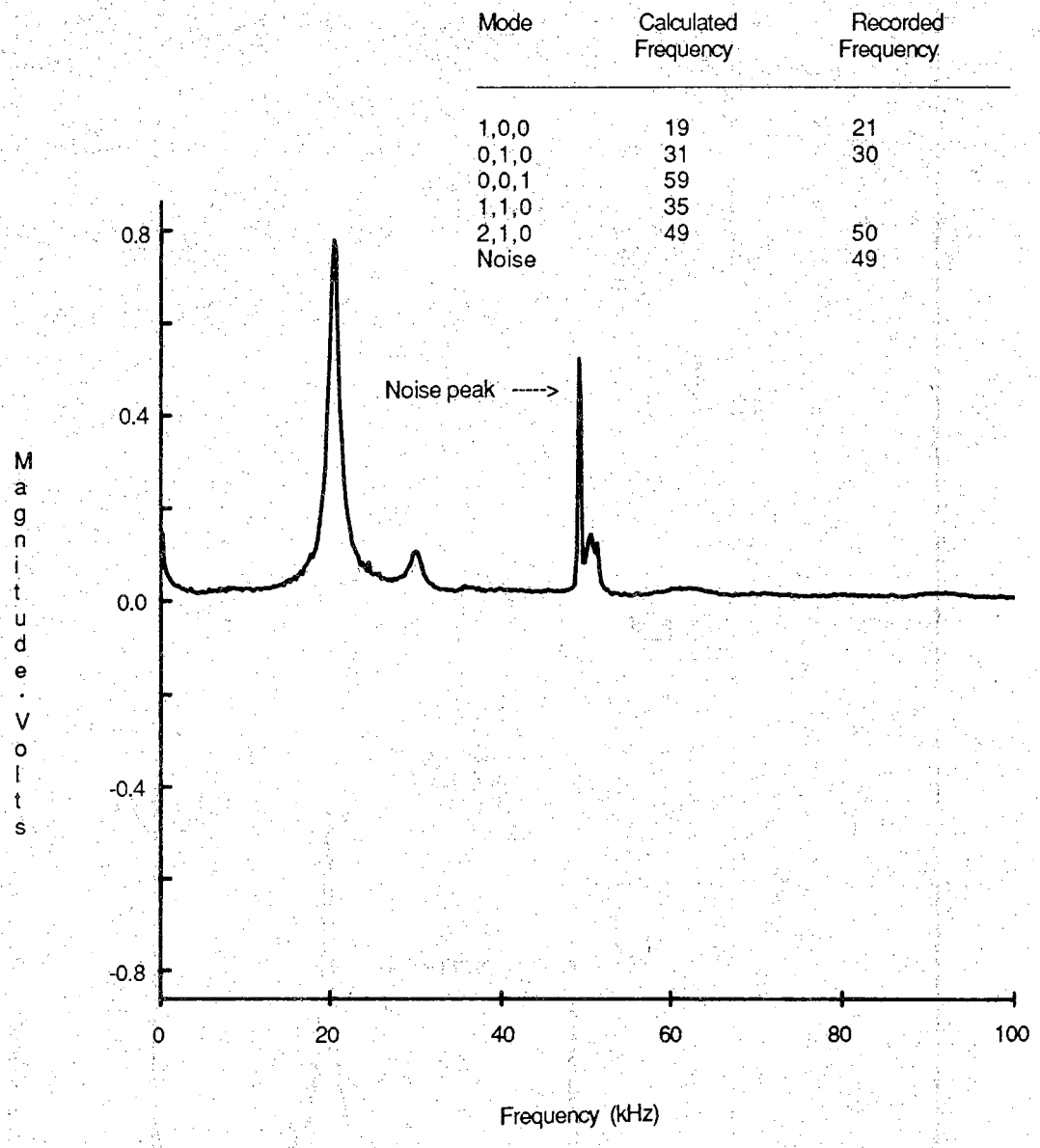


Figure 6. Recorded natural frequency modes in a rectangular block of cowpea cotyledon of approximate size 6.5 X 4 X 2 mm, compared to expected modes.

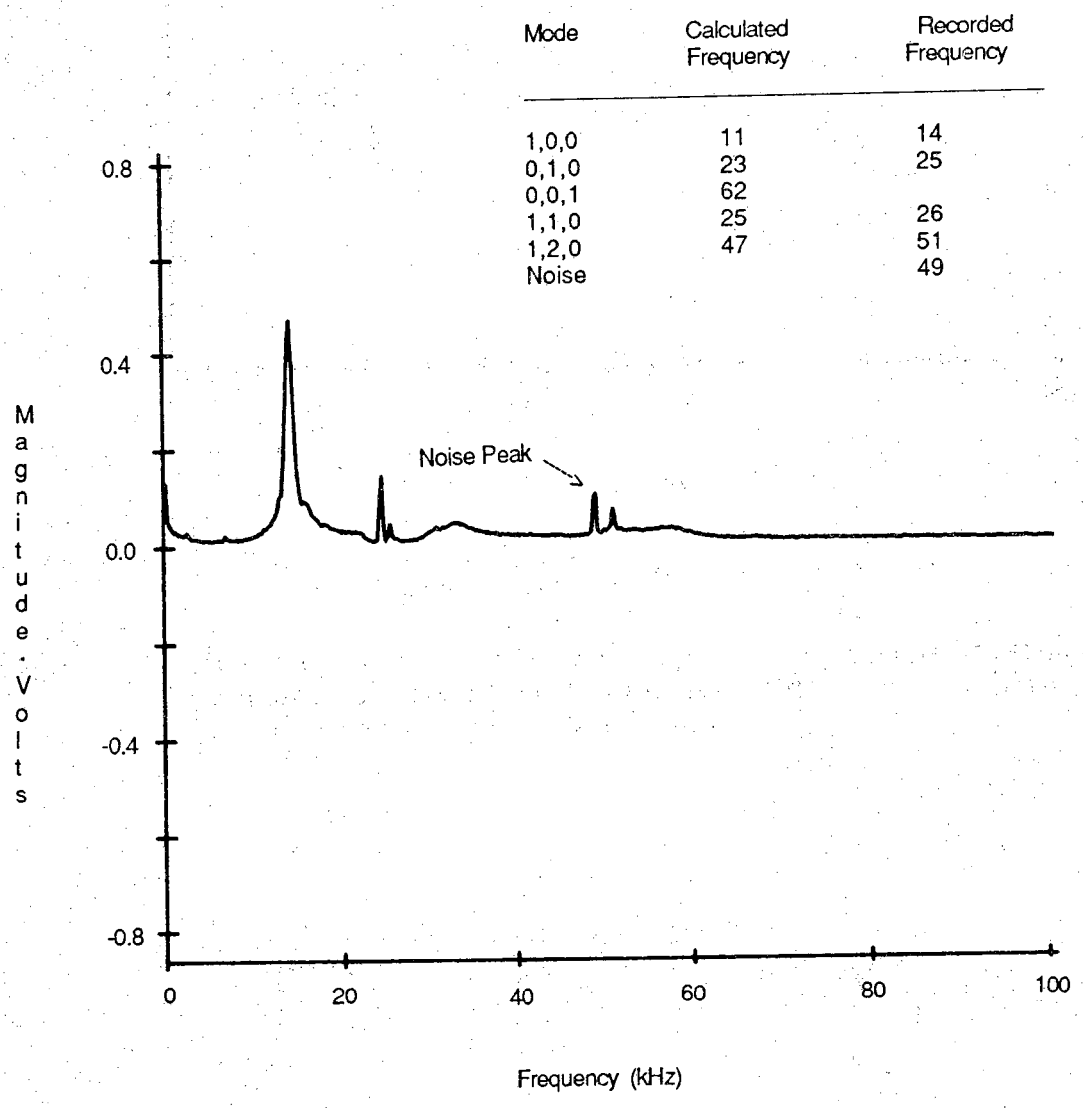


Figure 7. Recorded natural frequency modes in unaltered cotyledon, compared to expected modes in a rectangular cotyledon block of similar dimensions, 11 X 5.5 X 2 mm.

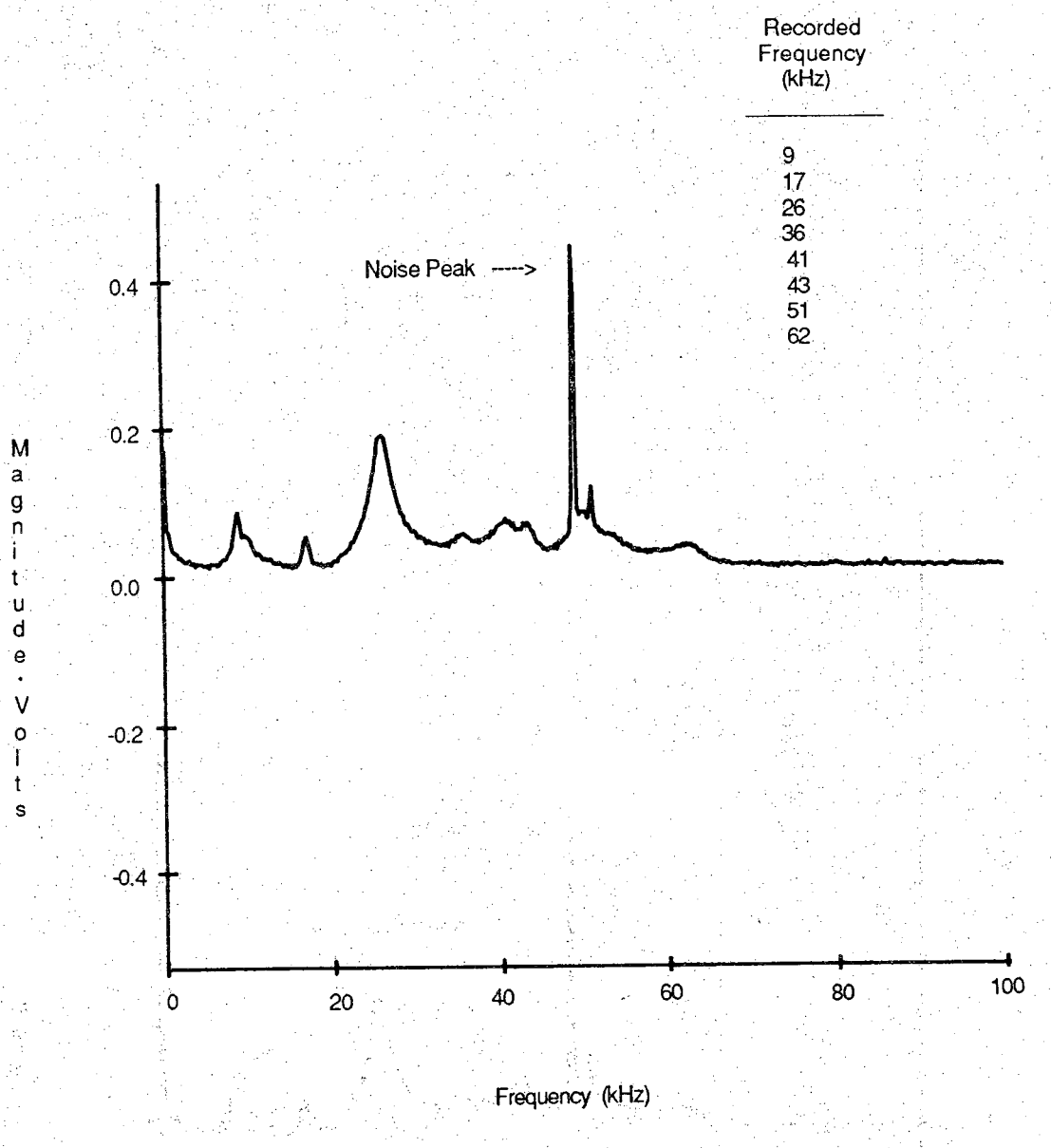


Figure 8. Recorded natural frequency modes in a whole bean with an approximate length and width of 11 X 5.5 mm, and approximate diameter of 5 mm.

one half to act as a mechanical load for the other. This slows the response of an individual cotyledon, which in turn lowers the resonant frequencies.

The resonances recorded for the kidney bean were similar to those for the cowpea. In addition to the sound velocity being higher in kidney beans than cowpeas, as mentioned above, the dimensions of the kidney bean are also larger than those of the cowpea, ($16 \times 7 \times 2.5$ mm). As a result, frequencies of the lowest order modes observed in a whole kidney bean were typically very similar to those observed in the cowpea. This was expected because the ratio of sound velocity to cotyledon length in the kidney bean is roughly equal to that ratio for the cowpea.

The higher order modes were more prominent in the kidney bean, however, than in the cowpea. This is expected to be the case because attenuation typically increases with frequency, and is generally higher for softer materials. Because the cowpea is somewhat softer than the kidney bean, the magnitudes of the higher order frequency components should be expected to drop off more rapidly in the cowpea than in the kidney bean.

2.2 Determining the Signal Source

The ultrasonic emissions from cowpea weevils residing in cowpeas and bean weevils in cowpeas and kidney beans were examined in an effort to determine the properties of the sounds generated by the insects. To acquire an undistorted waveform representing these sounds, a wide band ultrasonic transducer, made by Industrial Quality, Inc., [10], was placed in contact with the seed housing the insect, (see Appendix A). Sounds were recorded in the frequency range of 1 to 500 kHz. A typical signal generated by a cowpea weevil in a cowpea placed against the transducer is shown in Fig. 9. The observed signals were characterized by bursts of energy in the frequency range of 5 to 75 kHz, skewed towards the lower frequencies. These observed spectra agreed with what was predicted in the above discussion. Each burst lasted on the order of several tenths of a millisecond, and they were separated by intervals of silence lasting between several milliseconds and hundreds of seconds, depending mostly on the insect age. Two narrow frequency bands which consistently contained significant amounts of energy were 7.5 - 12.5 kHz, and 30 - 50 kHz. Negligible amounts of energy were recorded in the frequency bands of 1 - 5 kHz and 75 - 150 kHz.

The received signals were determined to be the result of feeding activity. This conclusion was based on two sets of observations. First, by shaving away enough of the seed to observe the activity of the larva, it was determined that

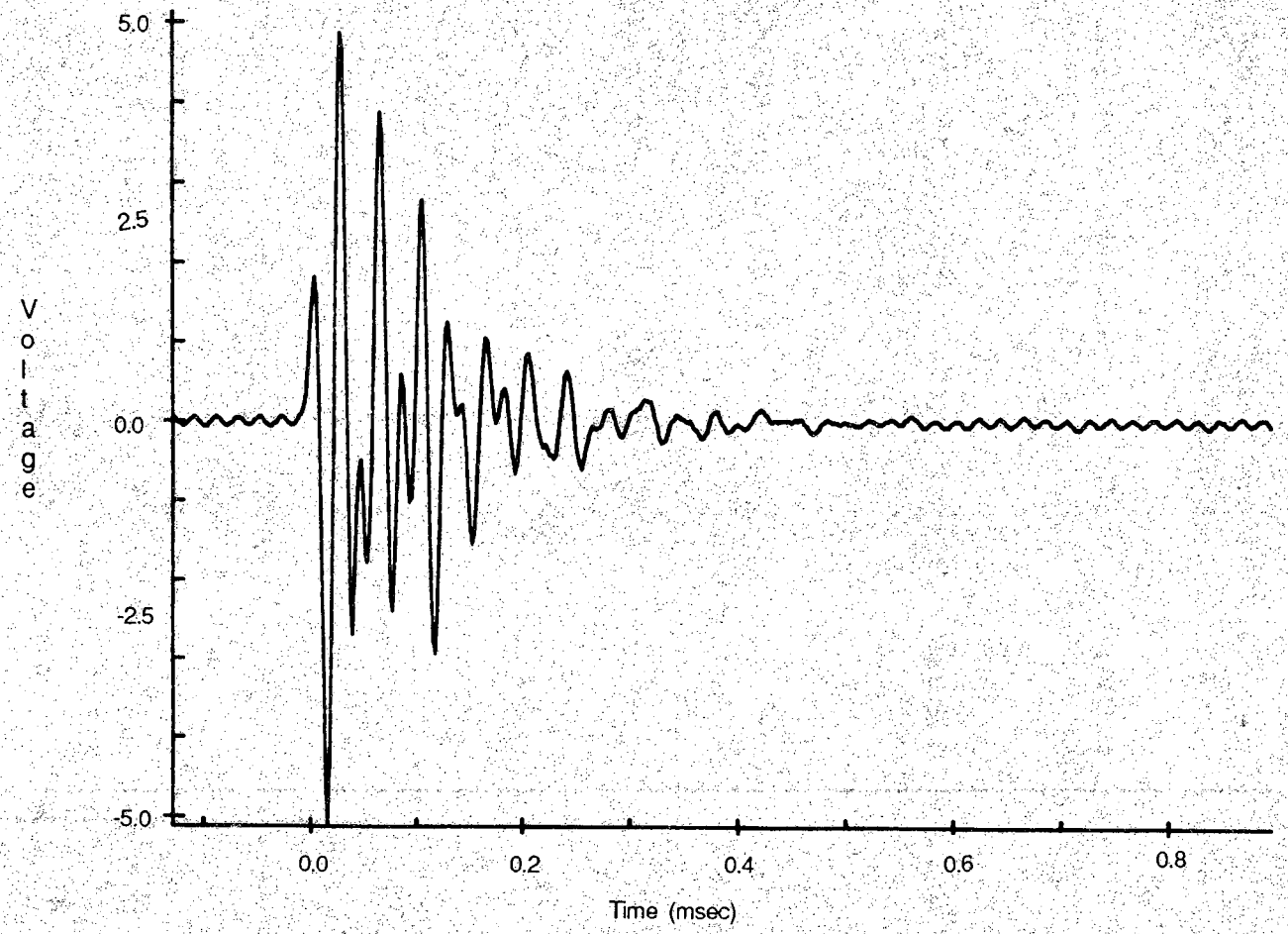


Figure 9. Transducer voltage representing the typical acoustic pressures resulting from a feeding event of a concealed insect in a cowpea.

no signal was generated by the general movement of the insect, [11]. The signals were generated only when the insect appeared to be feeding on the seed. Second, no signal was generated during the periods when the insect does not feed. These periods include the embryonic, pupal and adult stages, as well as the molting period preceding each larval instar.

Although the movements of the insect were briefly observed as described above, the mandibles of the insect were hidden from view, and the exact mode of feeding could not be determined. However, because the signals received were short impulsive bursts rather than prolonged scraping sounds, the signal was assumed to be the result of a fracture of the bean. For this to be the case, the spectrum of the signal would reflect the impulse response of the seed housing the insect, and would be independent of insect anatomy. Observations supported this theory for the insects examined. The signals recorded from either insect species feeding on a cowpea were typically very similar, as shown in Fig. 10. However, markedly different signals were recorded from the same species of insect, the bean weevil, feeding in two species of beans which were expected to have different impulse responses, as demonstrated in Fig. 11. These results were typical; the observed spectrum was mostly a function of the species of seed housing the insect, and was not influenced by differences in the species of insect.

Although most of the signal energy is consistently contained in the above mentioned frequency band of 5 to 75 kHz, the shape of the spectrum can vary significantly. Any variable which could influence the impulse response of the seed would be expected to change the shape of the spectrum. The most obvious variables are the size and shape of the cotyledons. As was discussed above, these directly affect the natural resonances of the bean. Another such variable is the position of the transducer with respect to the seed. This is demonstrated in Fig. 12, where the same event was recorded on opposite sides of a seed, yielding substantially different magnitude spectra. Other possible variables include the position of the insect inside the seed, the moisture content of the seed, and flaws in the seed, such as breakage or damage from past infestations [12].

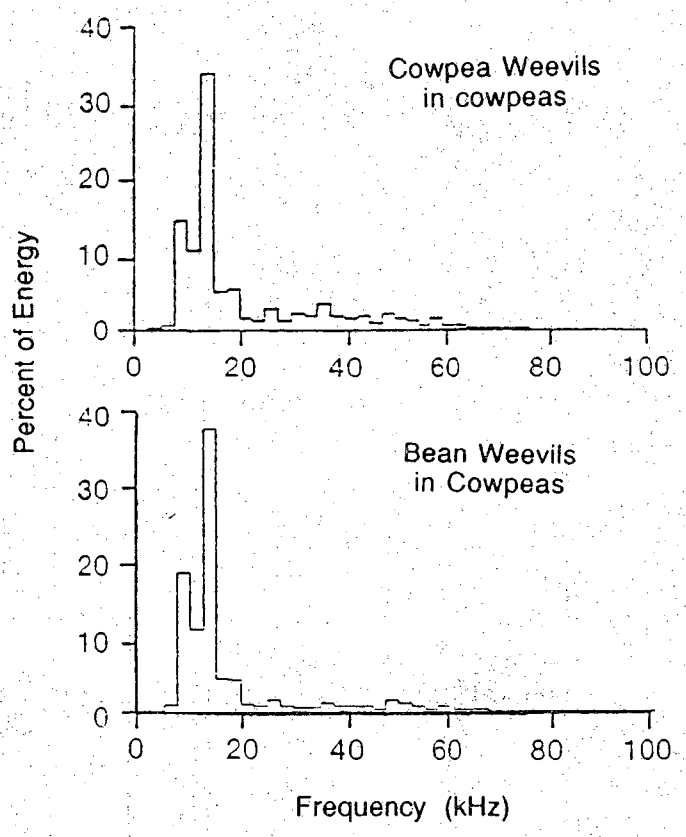


Figure 10. Comparison of energy spectra generated by two species of insects in cowpeas.

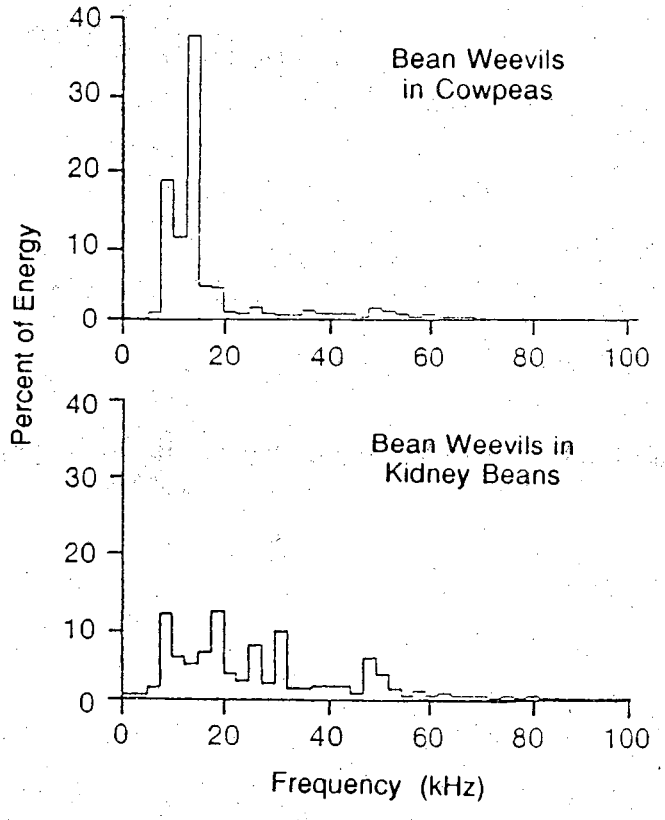


Figure 11. Comparison of energy spectra generated by bean weevils in two species of seeds.

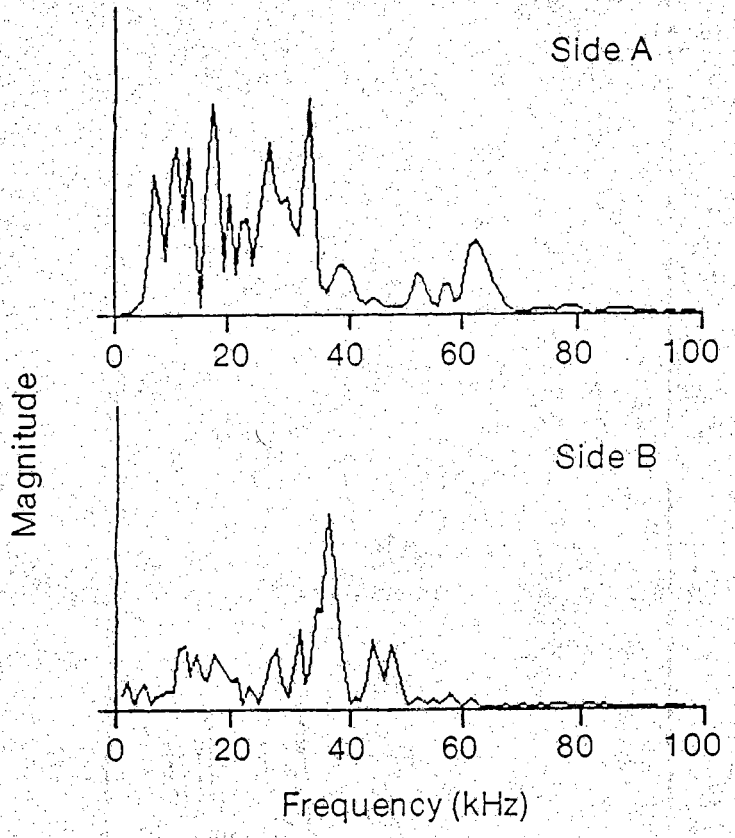


Figure 12. **Comparison of magnitude spectra as recorded on opposite sides of a cowpea.**

CHAPTER 3

AN ELECTRONIC SYSTEM FOR INSECT DETECTION

3.1 Choosing a System for Signal Reception

Several options are available for the design of acoustic signal receivers. However, several characteristics associated with the insect-generated signal must be considered to maximize the reliability of the system. Variations in the signal spectral characteristics result from variations in the natural frequencies of beans. Variations in the amount of received signal energy result from physical growth of the insect and the distance between the insect and the transducer. The variation in the spectral characteristics can increase the difficulty of positively identifying the signal as being insect-generated. The variations in signal energy increase the difficulty of predicting the amount of gain needed at the system input. For this research, a simple system was designed and constructed, keeping in mind the potential problems associated with these signals. The system designed and constructed for this research certainly has room for improvement, but at the cost of increased complexity.

A system was constructed which would take into account the above mentioned constraints, and allow a computer to store and analyze the signals. This patented device, [13], shown in the schematics of Figs. 13 - 20, made use of a highly sensitive transducer and a high gain input stage to maximize sensitivity to the signal. This amplifier was followed by a filter which passed only the frequencies which were expected to contain energy resulting from insect activity. The next stage was a full-wave rectifier and low pass filter which acted as an envelope detector/demodulator. This type of system was used because the signals were modeled as the physical response of a seed to an impulsive signal, as was discussed in Chapter Two. Thus, once the signal was received, the spectral properties of the signal contained no information, and the signal could be transformed back to an impulsive form in a lower frequency band. These band-limited impulses could then be monitored with an audio

circuit for immediate feedback to the system operator, or with the analog to digital converter of a computer to allow for a detailed analysis of the signals.

3.2 Extracting the Signal from the Noise

The first problem taken under consideration was that of extracting the signal from the noise. This can be difficult because the the insects generate very little signal energy. This should be expected because the insect larvae are extremely small, much smaller than the seed that houses them, as was demonstrated by Fig. 3 and Table 1. For this reason the system must have high sensitivity to acoustic signals. Of course, when one increases the sensitivity of a system to a low energy signal, system sensitivity increases to background noise as well. To minimize the effects of noise, the spectral properties of the insect and noise signals must be compared, and the system should be designed to extract the signal from the noise.

In most locations where grain is stored and tested, acoustic background noise is dominated by energy in the audible frequency range. Typical noise sources at these locations include engines and rotating machinery operating at hundreds to thousands of revolutions per minute, vehicle movement, and human and animal voices, to list a few. These noise sources seldom contain energy at frequencies above 20 kHz. Thus environments which seem relatively noisy by standards of human perception are often relatively quiet at higher frequencies. Because signals generated by insects in cowpeas and kidney beans contain significant amounts of energy at frequencies above this audible range, the susceptibility of the receiver to noise could be kept low simply by selectively monitoring the frequencies where little noise is present. The benefits of such a system could easily be lost, however, in certain environments. Acoustic noise at the frequencies above 20 kHz can be generated by forceful metal-to-metal contact or by damaging rigid structures.

One problem which can be more difficult to avoid is that of electrical noise. Electrical noise in the frequency range of 20 to 75 kHz is often caused by the fruits of modern technology, such as computers or fluorescent lights. This noise can generally be eliminated by properly shielding the transducer and seeds under examination. Of course, electrical noise can only be reduced to a certain degree, before thermal noise places a hard limit on the minimum signal magnitude which can be detected.

In addition to minimizing the received noise, it was equally important to maximize the received signal energy from the insects. This was done by mechanically coupling the ultrasonic transducer with the bean housing the insect. Though they did not need to be in direct contact, the amount of signal energy received was maximized when the distance between the insect and transducer was minimized.

3.3 Designing a System for Signal Reception

A transducer was selected which would minimize susceptibility to noise, while maximizing sensitivity to insect-generated signals. The transducer selected was a 40 kHz narrow band, miniature air ultrasonic transducer manufactured by Massa Products Corporation, (see Appendix A). A narrow band air transducer was chosen because of its high degree of sensitivity to acoustic energy. Its center frequency of 40 kHz was chosen because that was in the center of one of the frequency bands which consistently contained significant amounts of signal energy, as was discussed in Chapter Two. This center frequency, however, was not of critical importance because when the seed was placed in mechanical contact with the transducer, the sound was directly coupled to the piezoelectric element, and the transducer was not nearly so discriminating in the frequencies it received. The desired elimination of broad band noise could then be achieved in the later stages of the system, in the form of a bandpass filter.

The first stage of the electronic receiver was a low-noise, high-gain preamplifier. The duty of this circuit was to add enough energy to the signal so that any noise added by later stages of the system would be inconsequential. The amount of gain used at this stage was limited by the magnitude of the thermal noise. The input impedance was set at 4000 Ohms to match the impedance of the transducer. With this input impedance, the RMS voltage of the thermal noise within the frequency band to be examined was typically on the order of one microvolt at the preamplifier input. This value was calculated using Eq. 3, [14]:

$$V_{RMS} = \sqrt{4kTRB} \tag{3}$$

Where k was the Boltzmann constant, T was the temperature of 300 Kelvin, R was the input impedance in Ohms, and B was the bandwidth of several tens of kiloHertz. Thus, any transducer signal of lessor magnitude could not be discriminated from noise.

The magnitudes of the transducer signals generated by the feeding activity of the youngest larvae were seldom more than an order of magnitude greater

than the noise voltages, so a large amount of gain was needed at this stage. Older larvae generated far more signal energy, enough that they could easily drive the previously required high-gain amplifier into saturation. For these insects, a preamplifier with a lower gain was used at the system input. In all, four different preamplifiers were used for insects with gains ranging from 73 dB for the youngest larvae to 31 dB for the oldest larvae. The schematics for these amplifiers are shown in Figs. 13 - 16. Although automatic gain control could have been used, in this laboratory system, the operator was responsible for deciding which amplifier to use based on the characteristics of the output signal.

Once the insect-generated signal was amplified to the point where it was strong enough to be easily processed, it was filtered to remove energy which was assumed to be noise. This refers to energy in the frequency bands which typically do not contain energy from insect signals. Because the laboratory environment in which this particular system was to be used was well controlled and had very little acoustic noise, a high pass filter was used with a cutoff frequency of 1 kHz. This circuit is shown in Fig. 17. Although the system was not specifically designed to have any specific upper frequency limit, signals over 100 kHz were heavily attenuated by the preamplifiers. Acoustic noise signals in this frequency range were generally very weak, and seldom was any noise received. The resulting system was highly sensitive to insect signals, because virtually no insect energy was discarded by this filter. Other systems which cannot count on the luxury of a low noise environment will need to replace this filter either with a bandpass filter which would be least favorable to the local noise spectrum, or with an external noise sensor which could be used to subtract noise from the signal.

Following the high pass filter, the system uses a full-wave rectifier and low pass filter to demodulate the signal, which are shown in Figs. 18 and 19. The cutoff frequency of the low pass filter was set at 5 kHz for maximal smoothing of the rectified signal, while still allowing for maximal differentiation between separate signals occurring in rapid succession. The resulting output from this stage resembled an apparently random series of impulsive bursts of energy, band-limited to 5 kHz.

The final stage of the system was a comparator, shown in Fig. 20. The purpose of this circuit was to recognize and discard the peaks which were too small to have been generated by the insect, and were assumed to be noise. The decision threshold was operator adjustable, using the squelch control located in the full wave rectifier, as was shown in Fig. 18. This control simply added a

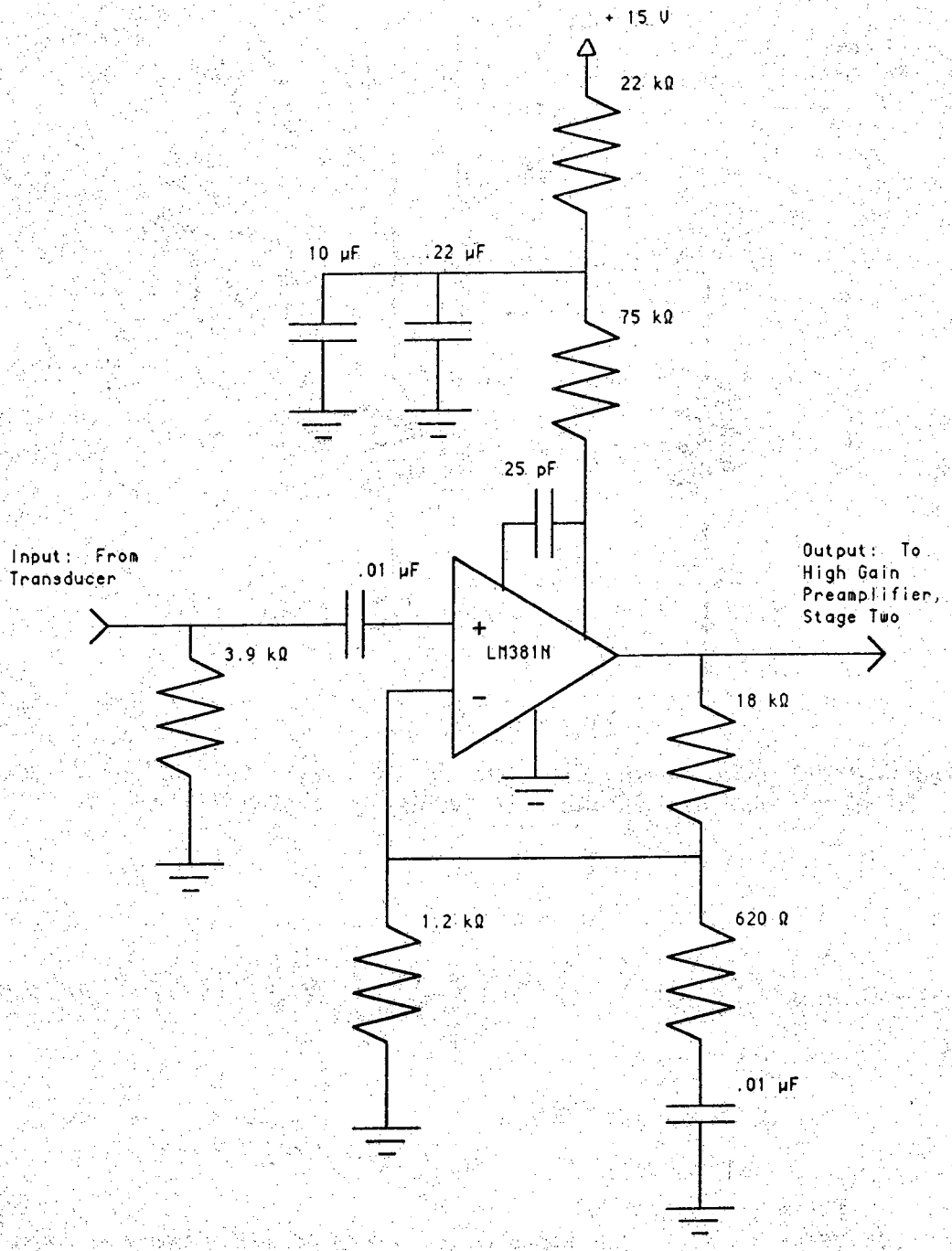


Figure 13. The two stages of the high gain preamplifier for the insect detector circuit. Combined, they amplify the signal by 70 dB.

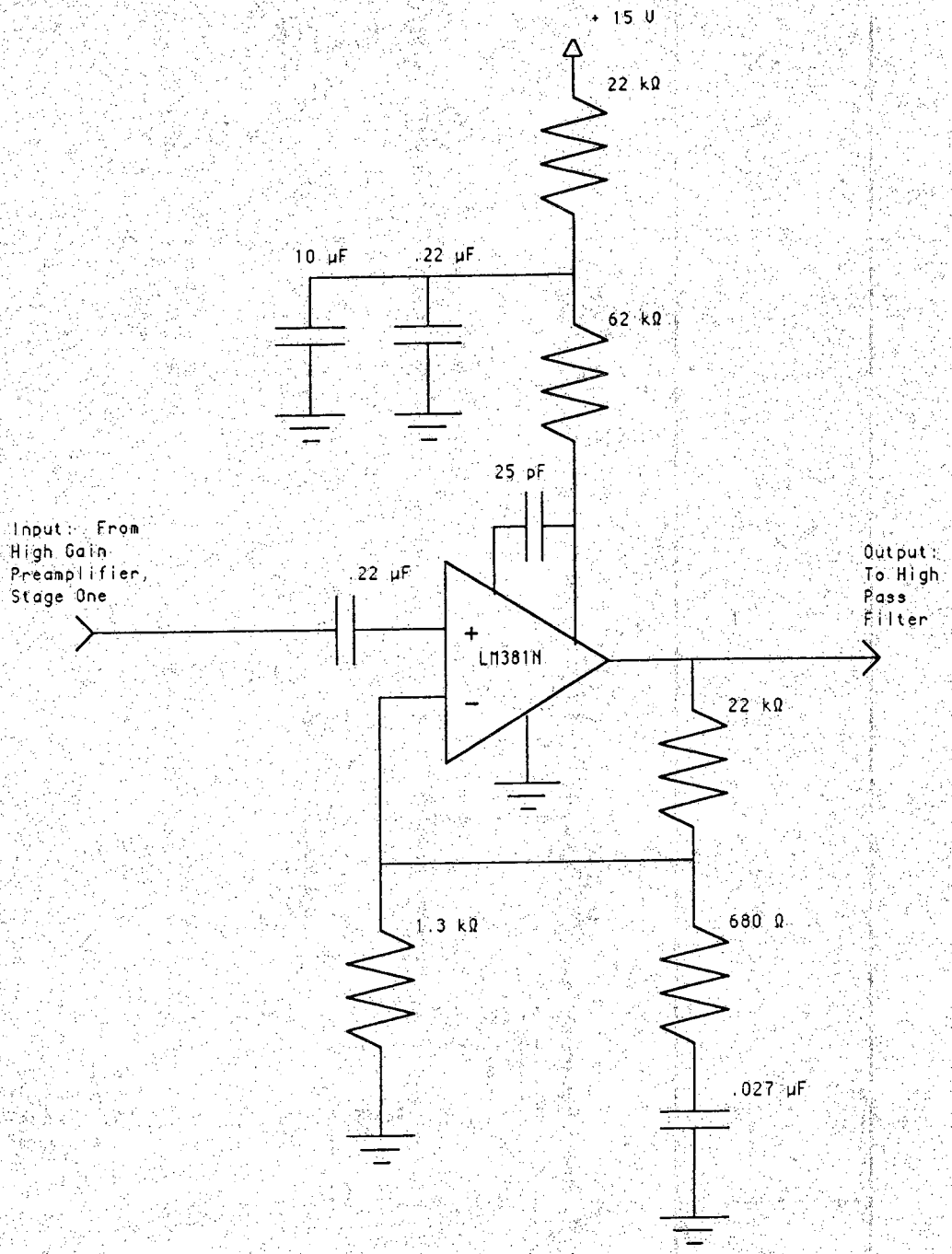


Figure 13, continued

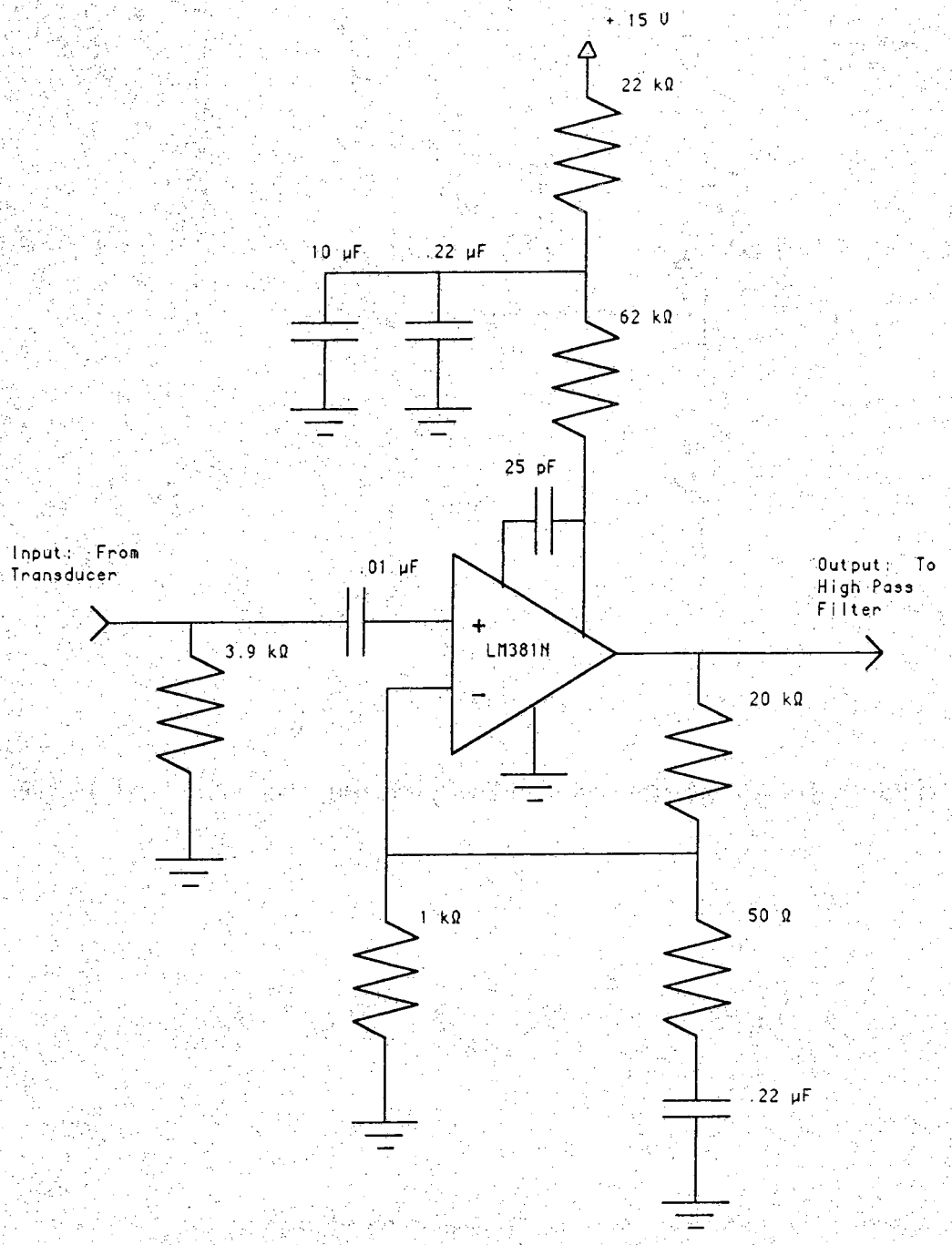


Figure 14. Low gain preamplifier for insect detector circuit, amplifies signal by 56 dB.

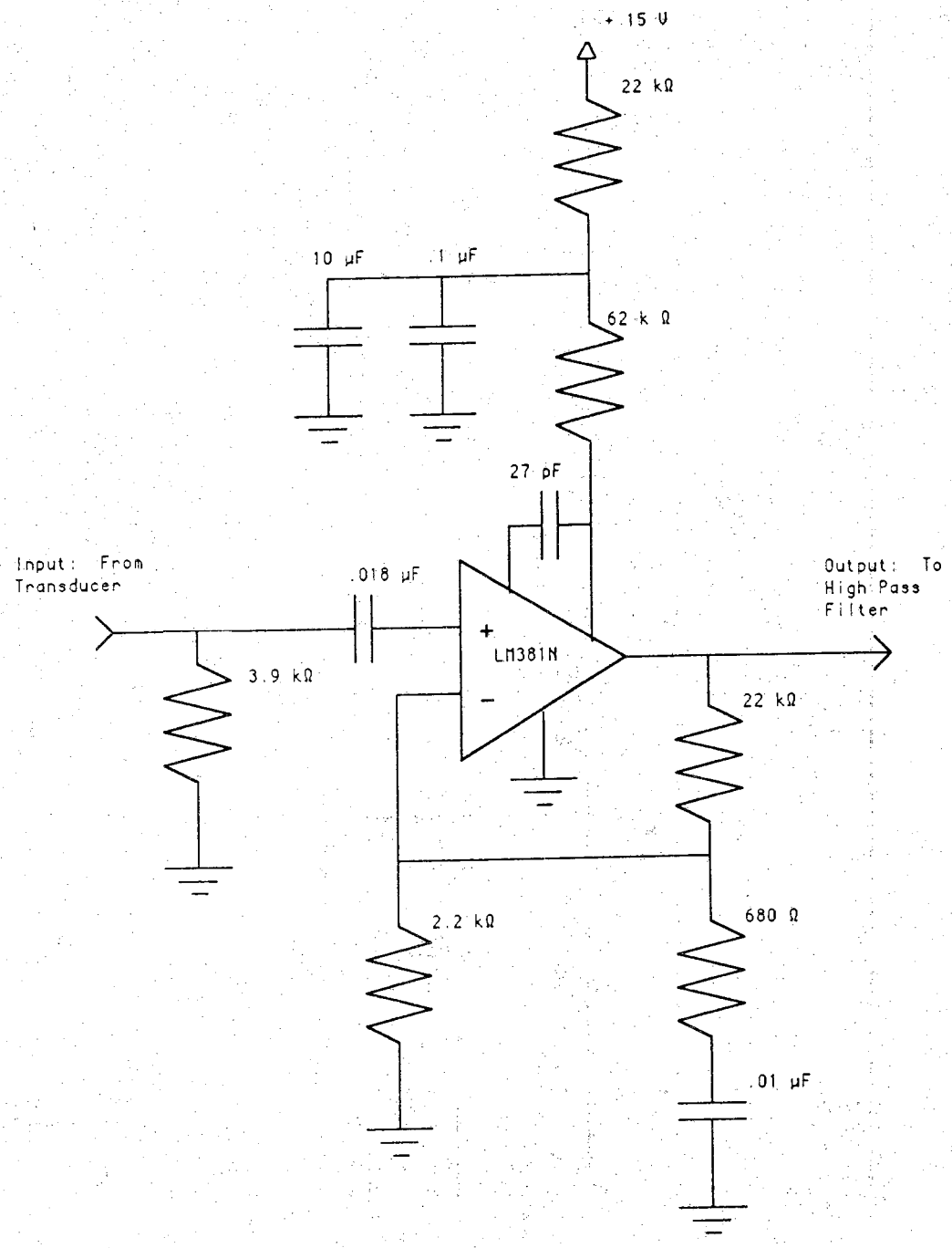


Figure 15. Very low gain preamplifier for insect detector circuit, amplifies signal by 31 dB.

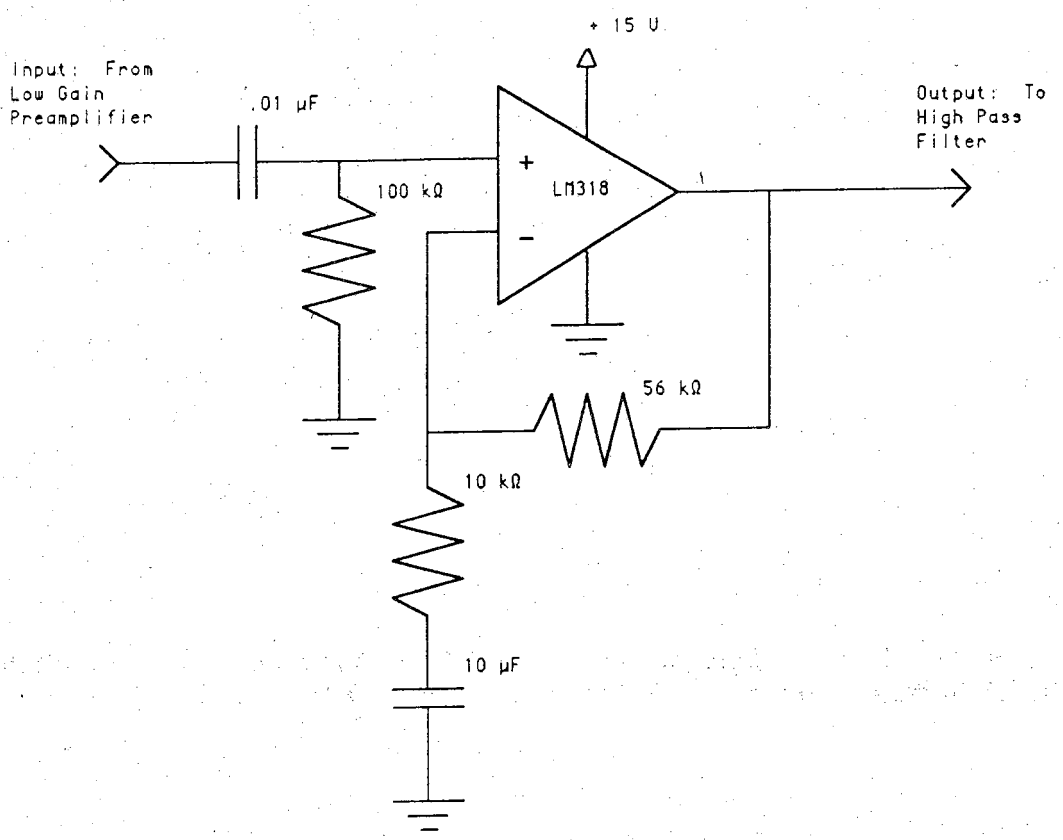


Figure 16. Booster amplifier which can be inserted in the insect detector circuit following low gain preamplifier for a total gain of 73 dB.

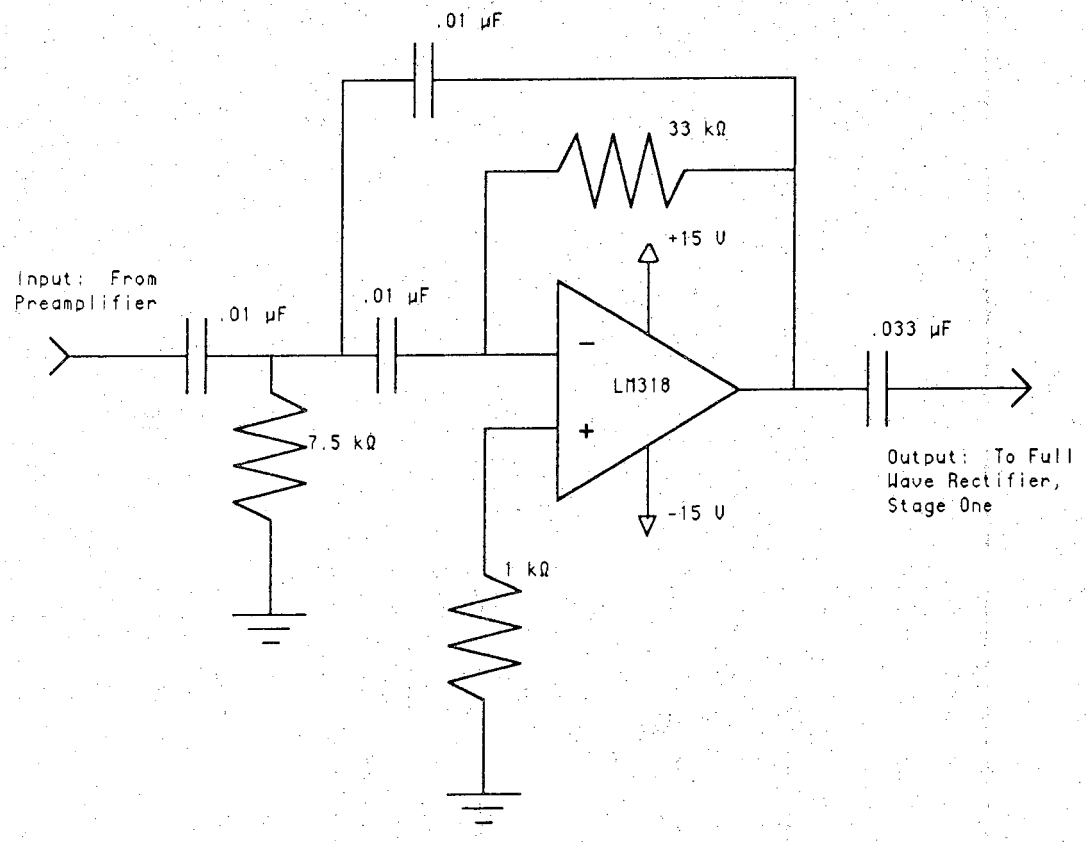


Figure 17. High pass filter for insect detector circuit which is adapted to reduce noise received from the surrounding environment.

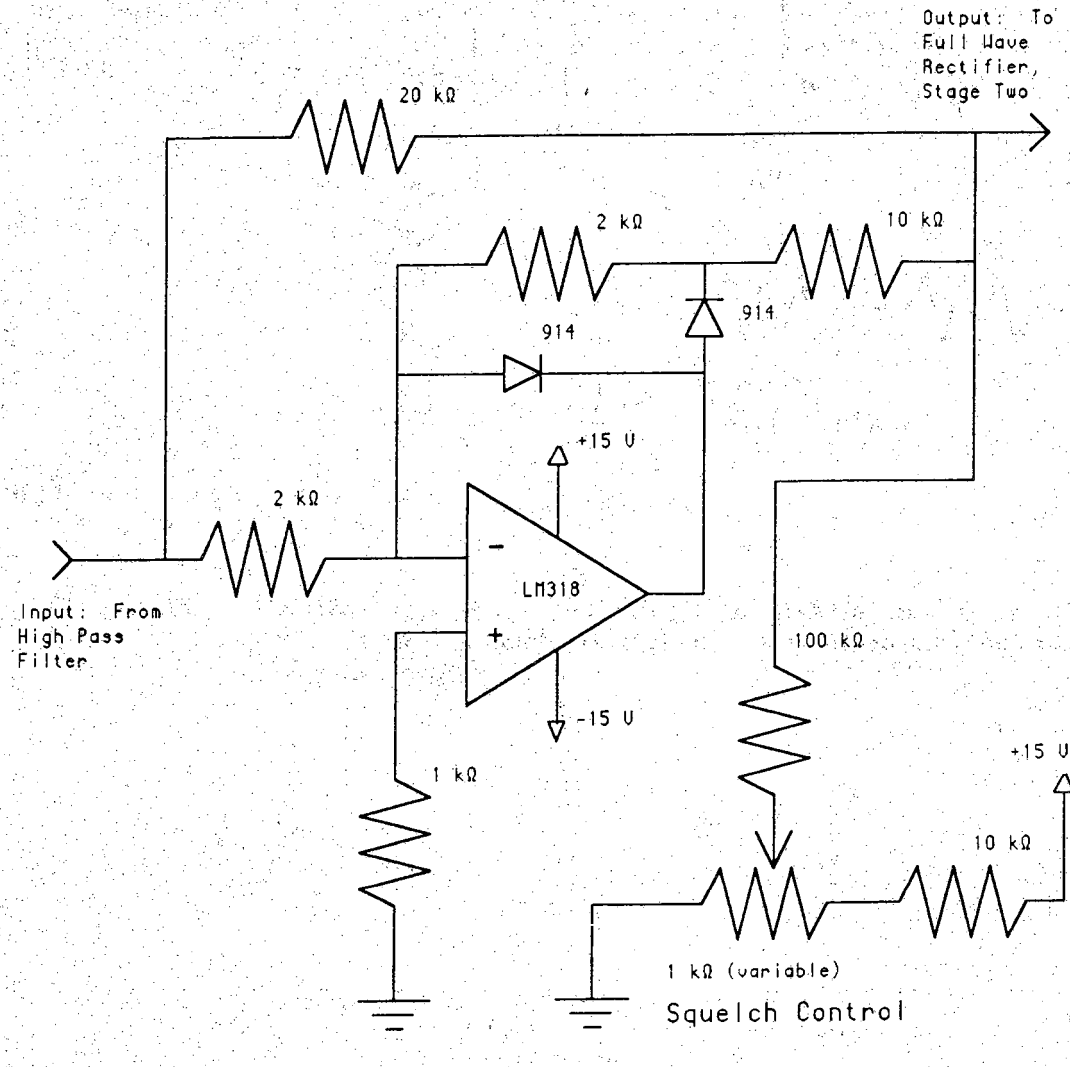


Figure 18. Rectifier circuit in demodulation section of insect detector circuit, with a squelch control for operator adjustment of signal detection threshold

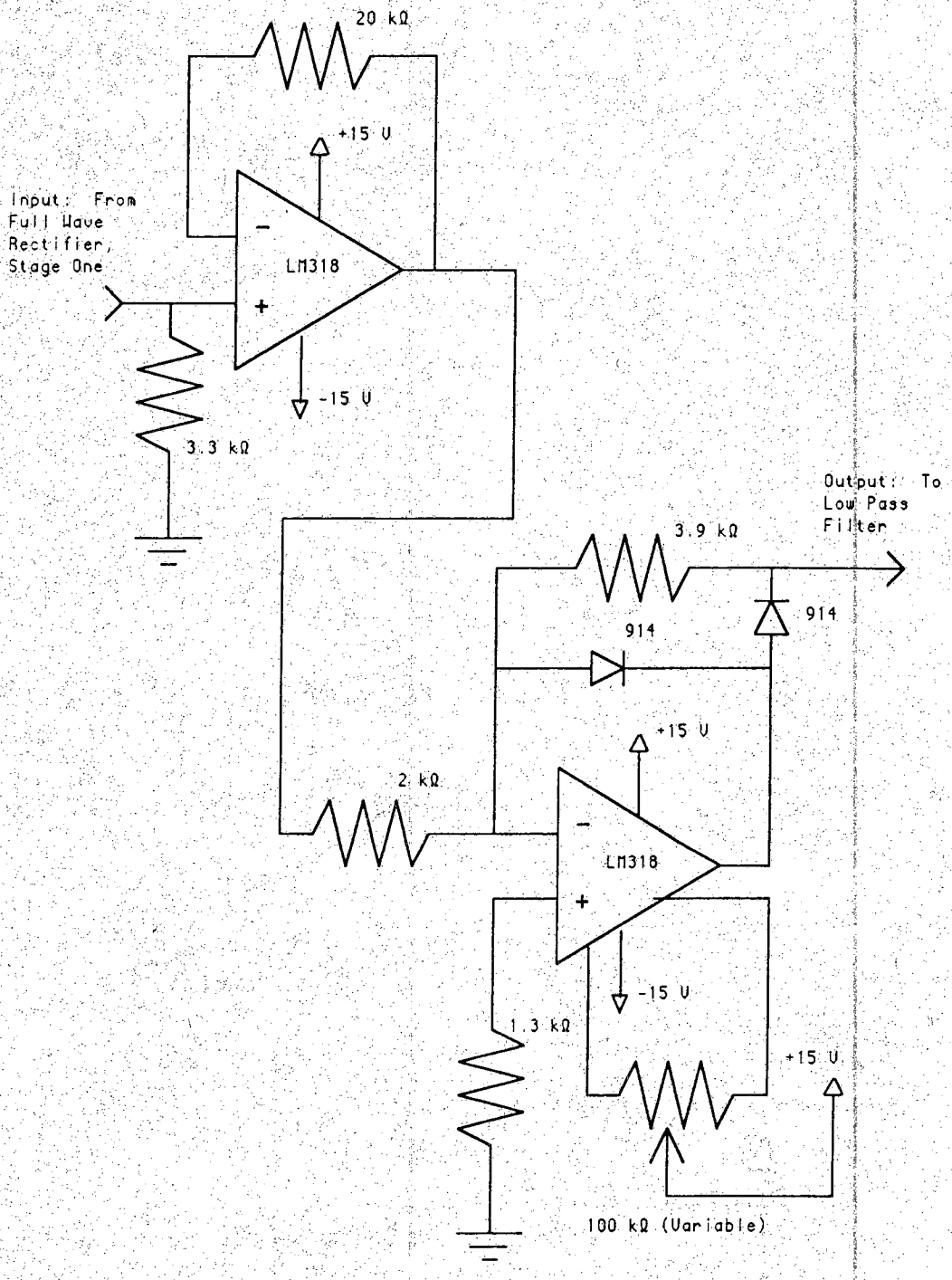


Figure 18, continued

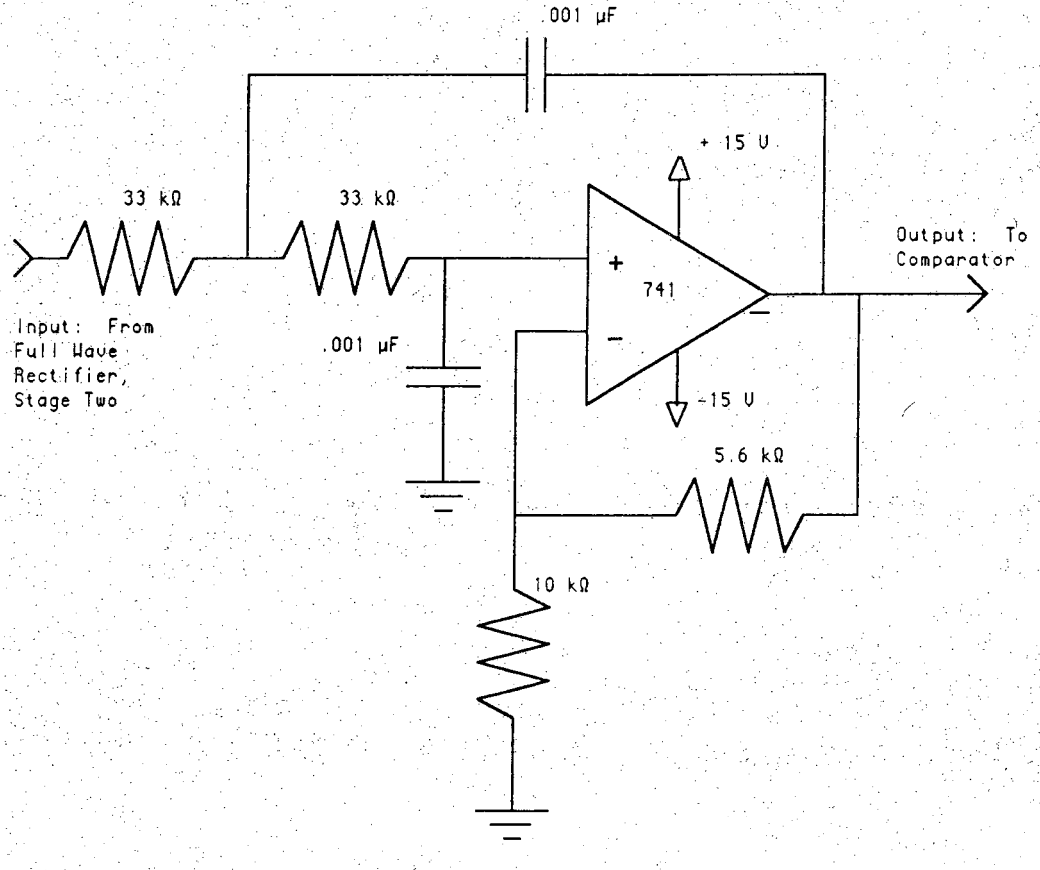


Figure 19. Low pass filter for insect detector circuit, with a corner frequency of 5 kHz.

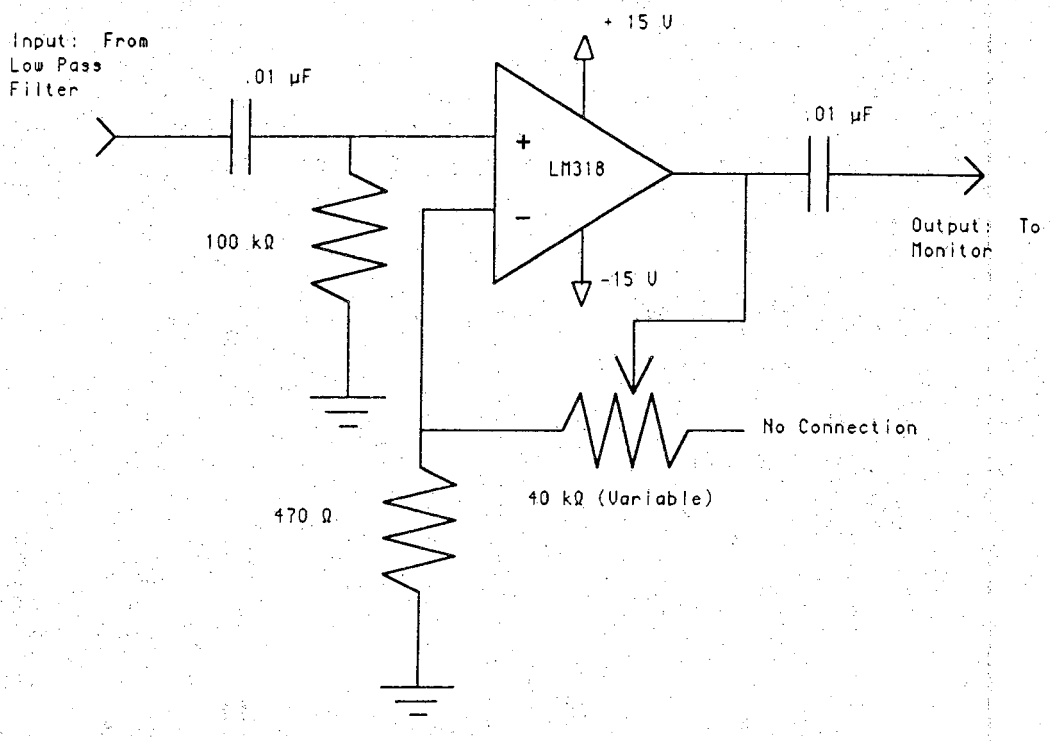


Figure 20. Comparator circuit for insect detector circuit, which provides a relatively noise-free signal at the circuit output.

DC offset to the signal so that the largest noise peak would be just under the comparator threshold. The resistance in the comparator feedback loop was also adjustable, which had the effect of controlling the amplitude of the output signal. This effect was a direct result of the impulsive nature of the signal applied to its terminals. This feature allowed the operator to adjust the system output to be within the allowed range of the signal recording system following the receiver. Once the adjustments were made to this circuit, they were left undisturbed, so that any changes in the recorded signal would be a direct result of changes in the insect-generated signal. The only adjustment made by the operator to offset changes in insect signal power was the exchange of preamplifiers, which was routinely documented.

The output of the receiver was AC coupled to many types of devices. This was done to protect the audio amplifiers and recorders, and to keep from wasting valuable bits in the range of the analog to digital converter. The value of the coupling component was chosen, keeping in mind the typical input impedances of the following devices, to refrain from attenuating the signal noticeably.

3.4 Methods of Monitoring and Recording the Signal

Once the signal was sensed, it was made available immediately as feedback to the system operator, and it was stored so that it could be analyzed at a later date. These two functions were carried out in several ways. The operator could monitor the signal in its audio form simply by applying the system output to the terminals of an audio amplifier and speaker, or the operator could monitor the signal visually by displaying the voltages on an oscilloscope screen. The signal data could be stored on several types of media for later analysis, including the paper of a strip chart recorder, the magnetic tape of an audio recorder, the down-loaded memory of a high-speed digital oscilloscope, or in the memory of a computer using a analog to digital converter. The benefits and drawbacks of each of these methods are discussed in the following paragraphs.

Each burst of sonic energy received by the transducer was represented by a 5 kHz band-limited burst of energy at the system output. Thus, with the aid of any standard audio amplifier and speaker, the output could be used as an audible indication of the acoustic activity at the transducer. This was used as a quick test of the environmental noise before the insect was placed near the transducer, and as a quick test of insect activity. Certainly, it was also needed as a real time indicator for system malfunctions. While data was being recorded for later analysis, the signal could be simultaneously broadcast to the

operator who would immediately be alerted to any unusual signal. For its purposes, this monitoring method was extremely beneficial. The only drawback was that when the operator heard a burst of energy, occasionally it would be difficult to distinguish an insect-generated event from noise. However, more often than not the noise was easily distinguishable.

For those cases when one was not sure if a signal was the result of background noise or an insect, an oscilloscope may provide some additional insight. Insect-generated signals often took on typical characteristics and resembled the signal exhibited in Fig. 9. Then the demodulated version of the signal also took on typical characteristics. Signals which did not fit in these typical signal molds could then be assumed to be caused by outside noise.

For most of the data analysis, the system output signal was measured with an analog to digital converter, (ADC), and the values could be stored in the computer memory. The ADC used twelve bits of resolution, or 4096 levels. Because the signal contained energy at frequencies at least as high as 5 kHz, (the low pass filter was a single-pole filter with a 5 kHz corner), the sampling rate needed to be relatively high. The maximum sampling rate of the ADC, 25 kHz, was chosen so that the most accurate representation of the signal could be acquired. With this high of a sampling rate, one megabyte of memory could be filled in only 40 seconds, so only brief periods of data could be stored. In an effort to save more data for analysis, the data was compressed by programming the computer to act as a peak detector. Then the only data recorded was the magnitude of the peaks and the time at which they occurred. The program which collects the raw data, PEAKTIME.BAS, along with the Assembly language subroutine which it calls, PT.ASM, and the program to convert the data into real times and magnitudes, PK.BAS, are listed in Appendix B. This technique was effective, because the insect signals were modeled as a series of impulses, and this type of data could completely describe such a band-limited impulse as was output by the system. The drawback of this storage technique was that any output signal that did not resemble a band-limited impulse was then misrepresented.

If one wanted to closely examine individual events, the output signal could be captured by a digital oscilloscope. Then the frequency characteristics of the signal could be analyzed up to about 1 MHz. This data could be dumped to the memory of a computer for future use. The main drawback of this storage technique was that only a few seconds of data could be saved before all available memory was filled.

One method was available to store a lengthy, detailed version of the output signal. This was to record the signal on magnetic tape via an audio recorder. Then the exact shape of the output could easily be recorded up to the 20 kHz components. From this tape, individual events could be chosen for an in-depth analysis from an extended period of data. This technique, however, was time consuming and tedious, so it could only be used for a few events.

By using a strip chart recorder to monitor the signals, the operator could obtain an instant representation of an extended period of data which could be easily interpreted. Although this device generally can only handle frequencies as high as 100 Hz, it does indicate when the each burst of energy occurs, and it gives a rough indication of the magnitude of the event. Because of its slow response, this device represents all signals as impulses, like the computerized peak detector described above. The greatest benefit of this device is that it records long periods of data in a way that can be visually interpreted immediately.

For the vast majority of tests, the signal was monitored in real time by the operator, using the audio amplifier and speaker. Most of the data analysis was performed using the analog to digital converter of the computer, which was programmed as a peak detector. These two methods were certainly the most convenient, and efficient in terms of operator effort. Extensive use of any of the other methods would require extreme amounts of time spent by the operator or would require far more equipment than was readily available.

CHAPTER 4

CHARACTERISTICS OF INSECT SIGNALS

4.1 Discussion of Signal Variations

As each insect is a unique individual, each should be expected to feed in its own unique way. However, the similarities in anatomy, physiology, and instinct, exhibited by insects of the same species, dictate certain similarities in feeding habits. Along the same lines of reasoning, the differences between species of insects, or the differences between insects of the same species at various stages of development, should dictate certain differences in their feeding habits. Because their feeding activity is betrayed by an acoustic signal, one might expect to detect variations in feeding habits simply by analyzing the sounds which the insects emit. These variations can be correlated with differences in the species or the stage of development of concealed insects.

Differences in received acoustic signals may be caused by a variety of sources. The rate at which acoustic events are received should directly correspond to the rate at which the insect feeds. Similarly, the way in which the insect fractures the seed should also influence when events are received. Changes in the environment surrounding the insect could elicit a response from the insect in the form of altered feeding behavior. Insects can be expected to detect a wide variety of stimuli, including changes in the surrounding temperature, illumination, sounds, movements, or toxins in the air. If the insect considers these variations to be cause for alarm, the insect may cease all activity until it believes the danger has past. If the variations facilitate the internal processes of the insect, such as digestion, the rate of feeding may increase.

The correspondence between the events detected and the way an insect fractures a seed is an interesting example. If an insect bites off a portion of seed in one clean fracture, a single isolated event should be detected. If the first fracture of the bite does not completely free the particle of food, the muscular reflexes of the insect may cause additional fractures. Assuming that each fracture would generate an acoustic event, this scenario would generate several

successive events, with a rate determined by the reflex action of the jaw muscles of the insect.

4.2 Observations of Variations

Signals generated by cowpea weevils were monitored for extended periods of time using the system described in Chapter Three. Several cause and effect relationships were observed between changes in the environment and the feeding activity of the insect. Changes in the surrounding temperature produced changes in the feeding rate of the insect. This is normal in cold-blooded species; all activity slows as temperature decreases. If the temperature gets too high, however, this also inhibits activity. Two types of stimuli appeared to indicate to the insect that some form of danger was present. Casting a shadow over the seed, or any movement of the seed caused the insect to quit generating acoustic signals for a short period of time. Several minutes after any such disturbance, the insect typically resumed normal feeding activity. These reactions to stimuli were common to all insects tested, and no correlation was observed between aspects of its response, and the age or species of insect present.

Two parameters were found to consistently vary as a function of insect age, the magnitude of individual events and the rate of feeding. Certainly the magnitudes of the feeding events increases considerably with insect age, as was noted in previous chapters. However, the magnitude of the received acoustic signal falls off proportionally to the square of the distance between the insect and the transducer. Thus, unless the exact location of the insect is known, one can not predict the amount of signal energy generated by the insect. This problem would be most apparent for the case where a large group of seeds were being monitored simultaneously using a single transducer. In this case, if a low-magnitude signal was recorded, one would not know if a young insect was generating the signal near the transducer, or if an older insect was generating the signal some distance away.

The feeding rate, or more accurately, the number of acoustic events detected over a given time interval, increases with the stage of development of the larva, as shown in Fig. 21. However, one cannot expect to simply count the number of events per hour and draw conclusions about the age of concealed insects. This is because the number of events increases with the number of insects present, as shown in Fig. 22, [15]. Because this relationship is linear, if one could first identify the age of the insects present, then this relationship could be used to quantify the level of infestation.

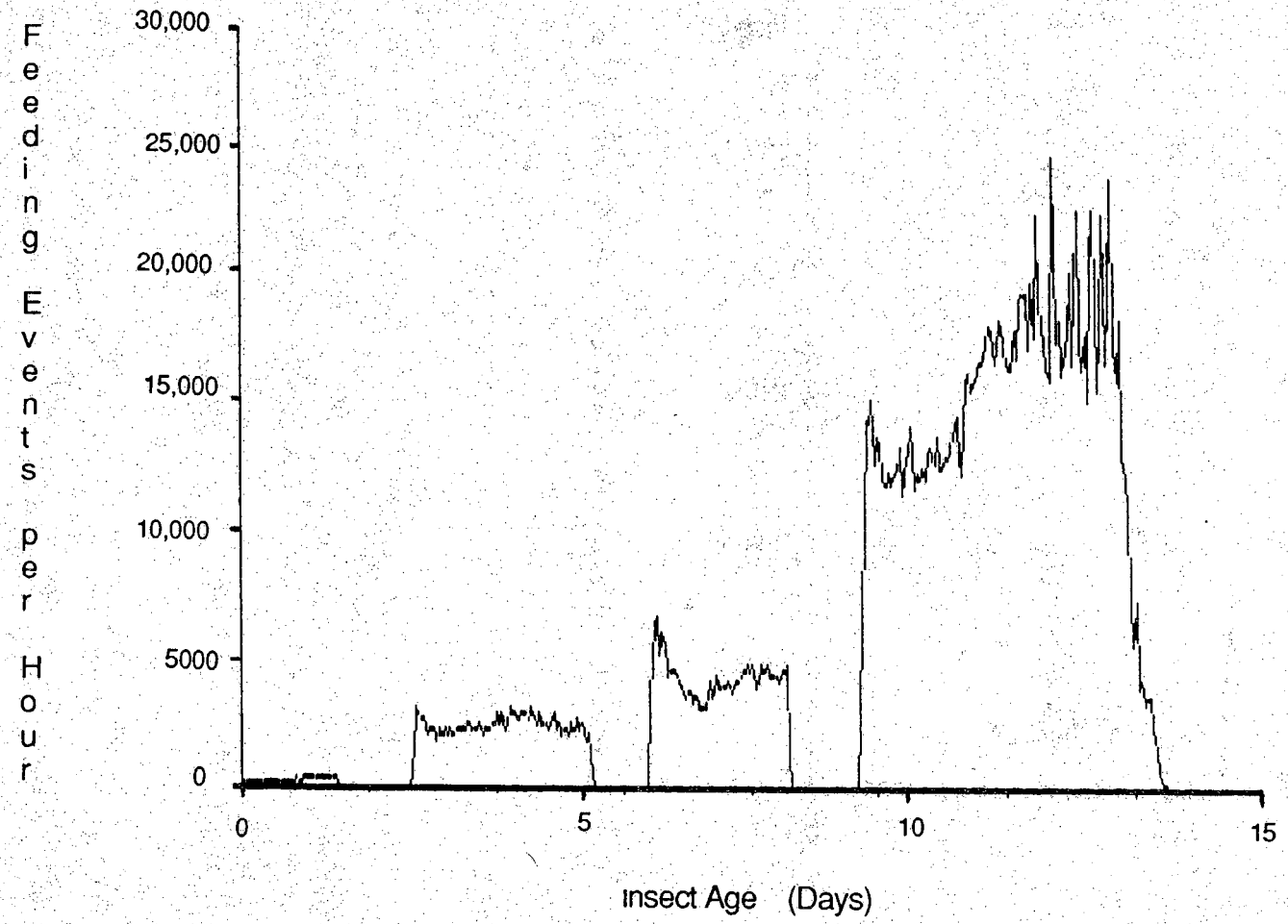


Figure 21. The feeding rate of a cowpea weevil for the four larval stages of development.

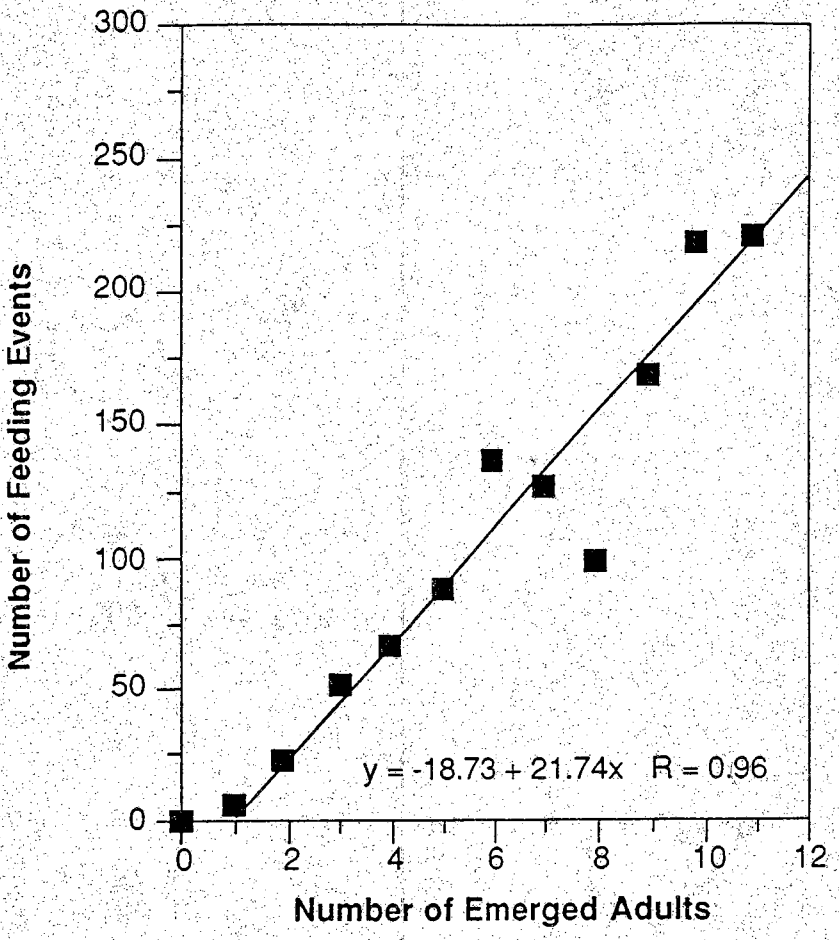


Figure 22. The linear correspondence between the number of insects present and the number of events detected for second instar cowpea weevil larvae.

The feeding pattern was also discovered to change as the insect aged. These changes can be observed in the five-second series of feeding events shown for three stages of development of the cowpea weevil in Fig. 23. The series for the fourth instar insect is more than just a simple random series of events. Events seem to be separated most often by intervals of silence lasting either one half or one tenth of a second. The second or third instar insects seldom exhibit a period of silence lasting as short as one tenth of a second. A typical five-second series of events is not shown for a first instar insect because only one or two events would occur in this interval, which is not enough to demonstrate any pattern. Periods of silence lasting on the order of one-half second are hypothesized to correspond to the time needed for the insect to reposition its mandibles between bites, [16]. If this is the case, then the period of silence lasting one-tenth of a second or less are most likely caused by multiple fractures of the seed during a single bite. These would be more common for older insects, which are expected to be able to take larger bites out of the seed.

The changes in the feeding patterns were documented by noting the length of each time interval of no activity between successive feeding events. Time intervals of certain lengths were noted more often than other lengths, and these common intervals changed as the insect aged. A great degree of success was achieved in using these variations to identify the age of the cowpea weevil. Similar variations were observed for other species as they aged. The bean weevil exhibited variations in common intervals of silence nearly identical to those exhibited by the cowpea weevil, indicating that these variations may be used to identify the age of bean weevils as well. However, because these variations were not identical to those of the cowpea weevil, they may also be used to identify the species of insect. In a preliminary trial, fourth instar insects of these two species could be differentiated with 86% accuracy by comparing the common intervals. Verifying the applicability of this test for species identification is left as an exercise for the reader.

Futile attempts were made in examining several other parameters to see if any additional information could be extracted from the acoustic signals. The relative magnitudes of the signals were studied, but no predictable pattern of change was observed for any variable associated with the insect. The combination of magnitudes and time intervals between successive events were examined. For example, when a relatively large event was detected, the pattern of the events immediately following were studied. Also noted was the response of the insect to a disturbance over the lifespan of the insect. Again, no predictable variations in the signals were observed for any variable associated with the insect.

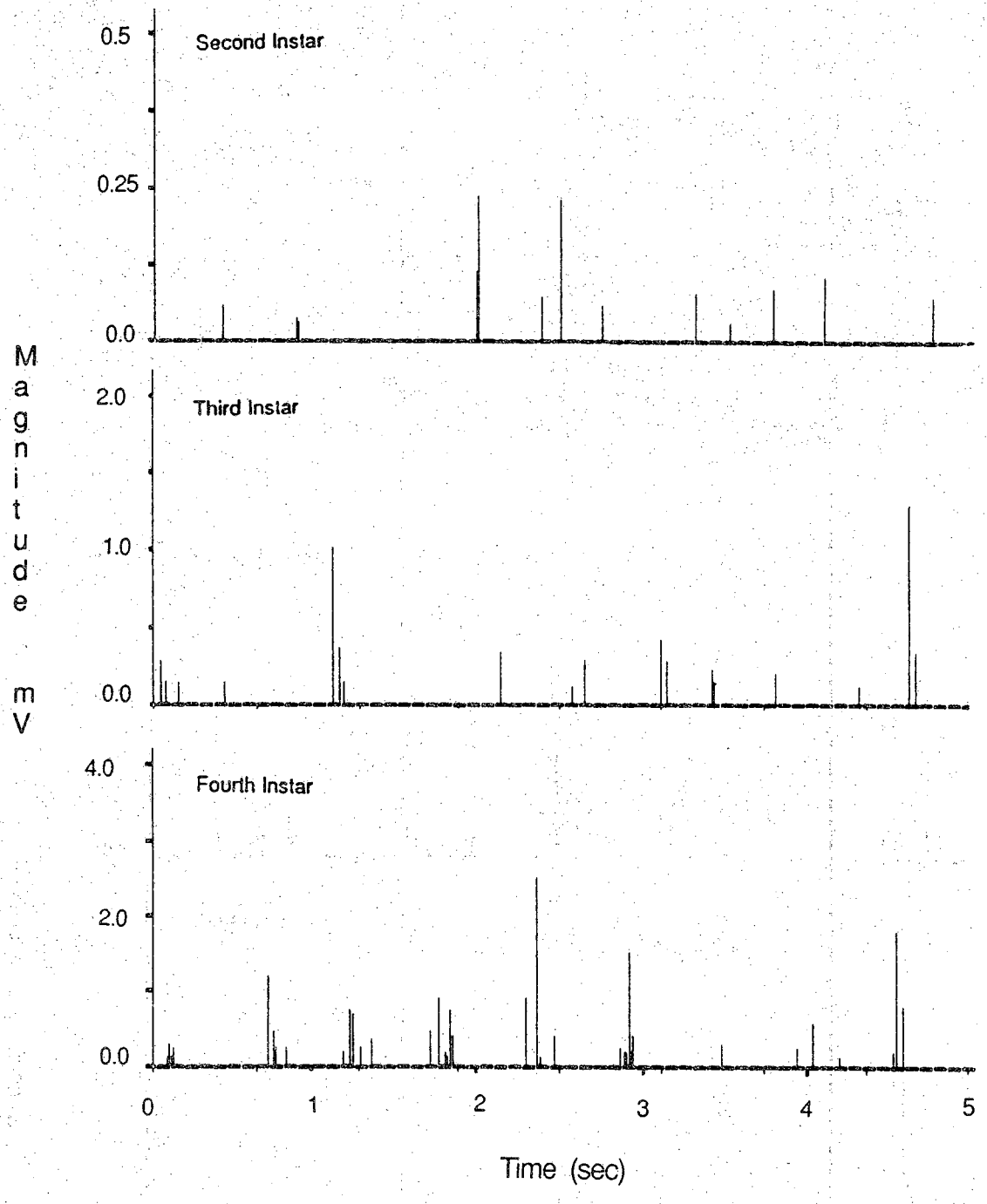


Figure 23. Five second series of events recorded at three stages of development of a cowpea weevil larva.

4.3 Feeding Patterns of Insect Larvae

The time intervals between each acoustic event was recorded and analyzed in an effort to identify the stage of larval development. The length of these time intervals ranged from 0.01 to 1000 seconds, and depending on the age of the insect, certain intervals were noted more frequently than others. These intervals were grouped according to their length, and a histogram was constructed to exhibit how frequently different intervals were recorded over a fifteen minute period. The range of possible intervals was divided into 80 bins based on a logarithmic scale, and a measured time interval of duration Δt was assigned to a bin according to Eq. 4.

$$\text{Bin Number} = \text{Integer}\left[16\log_{10}(\Delta t)\right] + 33 \tag{4}$$

For example, any interval in the range of 0.0100 to 0.0115 seconds would count as an occurrence for bin one, and any interval in the range of 100 to 115 seconds would count as an occurrence for bin 65.

Noticeable differences were observed between the histograms for insects at different stages of development. The younger insects exhibited a histogram with a single humped distribution, while the older insects exhibited a two-humped distribution. These differences in distributions were observed for both the cowpea weevil residing in cowpeas, and the bean weevil residing in cowpeas and kidney beans. These differences were even noticed in the case when more than one insect was present. The data from the preliminary tests showing these distributions are exhibited in Fig. 24.

The broad consistency in the distribution of time intervals indicated that this parameter could be used to identify the stage of development of the insects present, before any other information is gathered. However, before this technique could be used, several other causes of feeding pattern variation needed to be circumvented. Although the progression of variation of the distribution of time intervals was very consistent for the insects tested, the rate of progression was not. Two parameters could have a significant impact on how late in the life of the insect certain changes were observed: increasing the surrounding temperature, and changing the threshold for signal detection. Increasing the surrounding temperature, which increases the feeding rate of the insect, also accelerates the progression of change in the distribution of the histogram of time intervals. Increasing the temperature also increased the magnitudes of the acoustic signals. In fact, the magnitude of the events changed as a function of an indeterminate number of variables. This caused a problem, because increasing the number of events the system can detect changes the distribution towards that corresponding to an older insect.

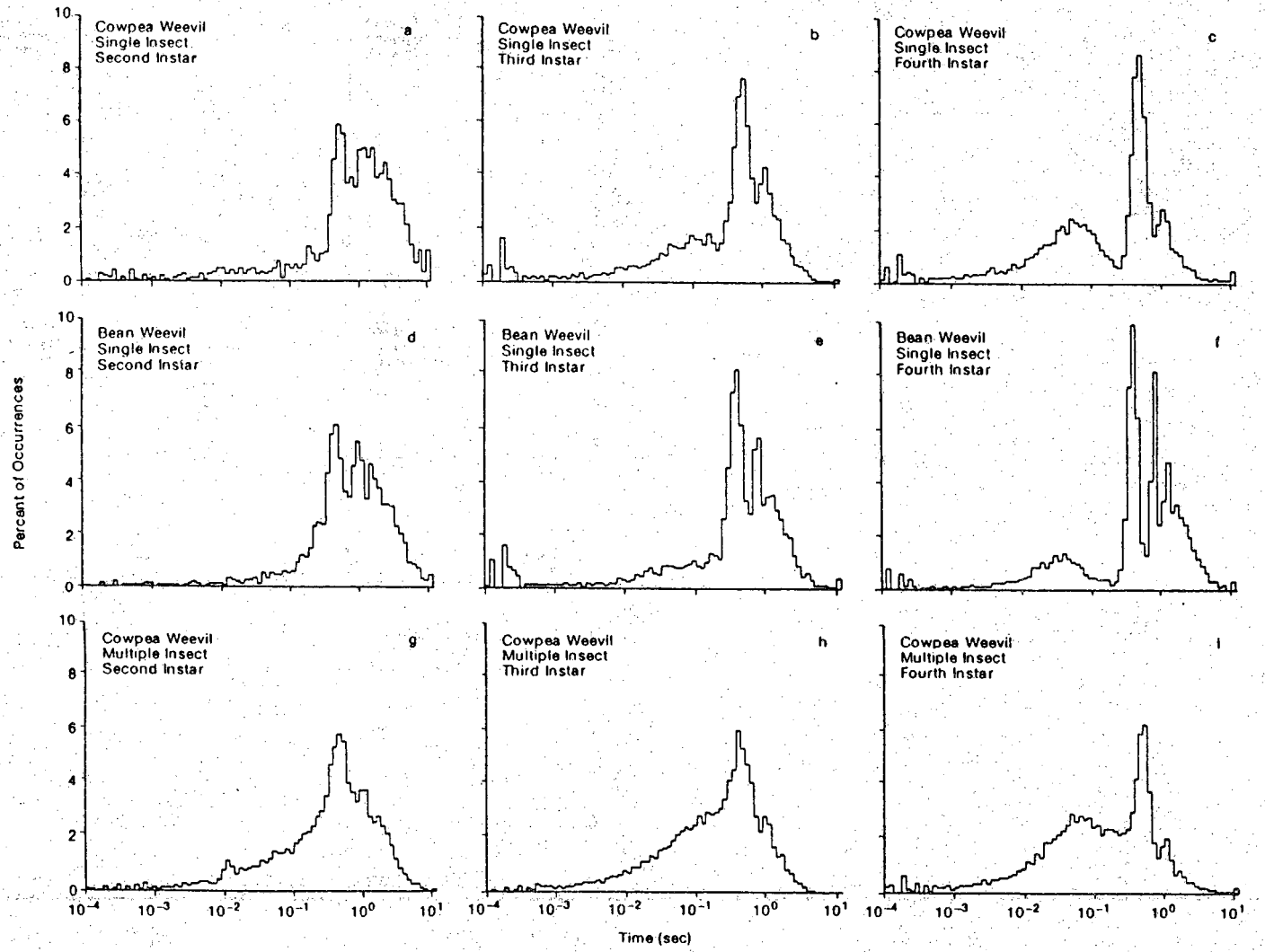


Figure 24. Typical histograms showing the distribution of time intervals between feeding events for cowpea weevils and bean weevils.

By varying either of the two above mentioned parameters, temperature or threshold, the histogram of a younger insect could be made to take on the characteristics associated with an older insect, or the histogram of an older insect could be made to look like that of a younger insect. An example of the former case is shown in Fig. 25. The cause of this is hypothesized to be the secondary fractures of the seed associated with a single feeding event. Recall that as the insect grows older, it is expected to take larger bites, which would result in more secondary fractures, which in turn result in acoustic events separated by periods lasting approximately one-tenth of a second. Assuming that not all secondary events are of the same magnitude, by raising the input threshold, the frequency of one-tenth second intervals would be decreased. This directly accounts for the changes in the distribution as a function of threshold. For this hypothesis to be correct, the difference between the relative amplitudes of each fracture during an individual feeding event would need to be small for older insects, but larger for the younger insects.

The threshold for detection of the acoustic events could not be held constant for all insects being tested. The reason for this, as discussed in Chapter Two, has to do with the wide range of signal magnitudes generated by the insect as it ages, in addition to the other causes of variation in signal magnitude. This wide range of magnitudes puts extreme demands on the dynamic range of the electronic receiver. As a result, if a system was designed to provide a strong output for the weak signals of the youngest insects, then the system would receive an extremely large number of events from the older insects, including many secondary events such as echos, which would distort the time interval histogram. To provide the operator with discrete options for the threshold of detection, the four preamplifiers described in Chapter Three were constructed, and an algorithm was derived to compare the magnitudes of the signals received with each. Then the operator could select the appropriate preamplifier for the magnitude of signals being received, and the computer could set a threshold at a level of the analog-to-digital converter appropriate for the preamplifier.

The timing and magnitudes of the received signals were also influenced by any disturbance sensed by the insect, as was mentioned above. Often, no signals were received immediately after a disturbance. After a minute or two, the insect began eating again, and the rate of occurrence of ultrasonic events soon returned to normal. The magnitudes of the received signals began at a lower level, and after several minutes returned to their typical values.

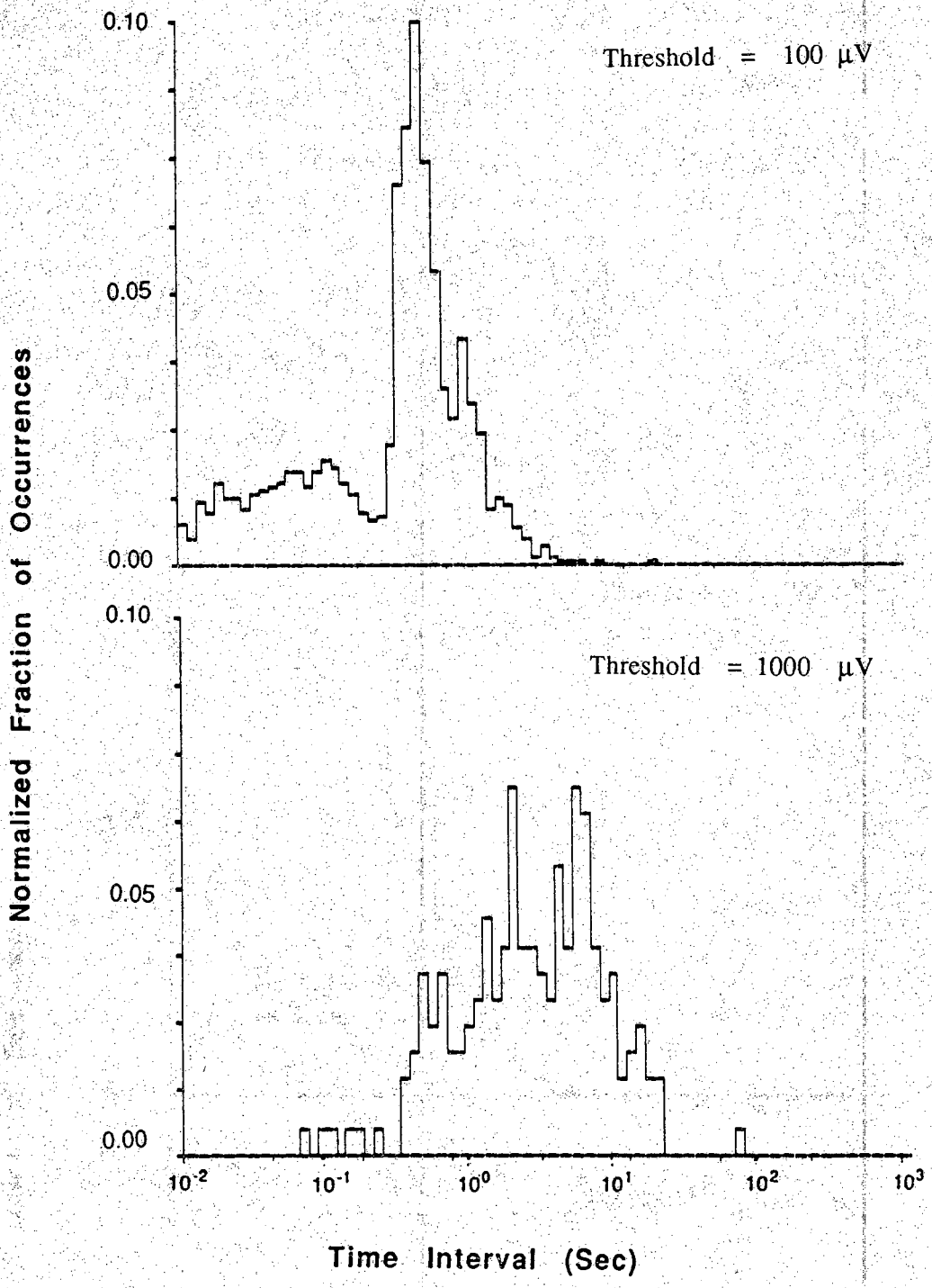


Figure 25. Two time interval histograms generated from the same series of events, using different software-imposed thresholds.

The variations described above were circumvented by using an empirically derived standard testing procedure. To overcome the problem of variations in magnitude, the input threshold was adjusted to a level relative to the largest event. An exact, discrete threshold level could be selected by the computer at the stage of the analog-to-digital converter. To overcome the problem of the reaction of the insect to a disturbance, data was ignored for a brief period after the insect was handled. By adjusting the relative threshold and the length of the pause before testing, the differences in the feeding patterns could be maximized with respect to the stage of development of the insect. The computer program performing the tasks as described below, PROC5G.BAS, is listed in Appendix B.

Based on observation, it was determined that feeding activity had consistently returned to normal within four minutes after the insect was handled. Thus, during the first four minutes after the infested seed was placed on the transducer, the feeding patterns were ignored. During this period, however, not all data was discarded. The signals were monitored to determine the magnitudes of the largest signals generated by the insect. This information was needed before a relative threshold could be set.

A relative threshold of one-third the magnitude of the second largest feeding event was chosen because this maximized the variation between the patterns generated by insects at the four stages of development. The largest event was ignored in case an abnormal event was detected. If no abnormal event was detected, then the largest events were approximately equivalent. For the next ten minutes, the feeding events were recorded for the purpose of constructing the time interval histogram. Once the threshold was set, the time interval histogram exhibited a predictable distribution, varying with the age of the insect.

A typical histogram distribution was empirically derived for each stage of larval development, (each instar), of the cowpea weevil, such that the entry in each bin represented the typical percentage of occurrences of each time interval range, with respect to the total number of intervals recorded. Each bin of the histogram was interpreted as a separate dimension in an 80 dimensional space of real numbers. Thus the histogram became a vector with an entry in each of 80 dimensions defined by the frequency of occurrence of each range of time intervals. This standard vector for each larval instar was normalized with respect to the Euclidean norm, and was saved for comparison. Then, when a new data vector, (the normalized histogram), is calculated for a cowpea weevil of unknown age, the standard vector having the minimum distance from this

new data vector, (measured using the Euclidean metric [17]), indicates the stage of development of the unknown insect.

Using the four standard normalized vectors shown in Fig. 26, the stage of larval development was predicted for cowpea weevils in 117 cases. The method described above correctly identified the instar of the insect in 83% of the cases, and in most of the remaining cases the prediction was within one instar of the correct stage of development. For example, a conservative prediction, defined as a prediction giving the correct instar or one instar older than the true age of the insect, was made a in 96% of the cases. Most of the errors were made when predicting the age of an insect that was near the start or end of the molting process. The computer program performing these tasks, PROJECTN.BAS, is listed in Appendix B.

4.4 Conditions Affecting the Accuracy of Predicting Insect Age

The above technique accurately predicted insect age under various conditions. Tests on insect cultures maintained at different temperatures, at 70 and 80 degrees Fahrenheit, yielded similar accuracies. Although each stage of development lasted several days, data could be recorded at any time during a stage of development without losing the high accuracy, (with the possible exception of one or two hours before and after each molt.) The variations observed between the histograms of insects at different ages was also apparent for the case where more than one insect was present. Although increasing the population tends to obscure the feeding patterns, the age of the insect can still be determined for moderate sized infestations. The main drawback of using this technique for the case when more than one insect is present is that the signals of younger insects would be obscured by the oldest insect present. This is a direct result of the smaller magnitudes of the events generated by the younger insects, as well as their smaller number of events.

The above successes were recorded for the cowpea weevil feeding in cowpeas. The bean weevil exhibited similar feeding patterns, but in order to identify the stage of development of this insect, a new group of typical histograms would need to derived. The most notable difference between the two insects was that for the cowpea weevil, a plurality of events were separated by intervals of approximately 0.5 seconds, whereas for the bean weevil, the most common time interval was closer to 0.4 seconds. Another significant difference was that the bean weevil had a lower percentage of events separated by a pause lasting longer than one-half second. This result is most noticeable when one counts the number of events over a fixed period. The bean weevil

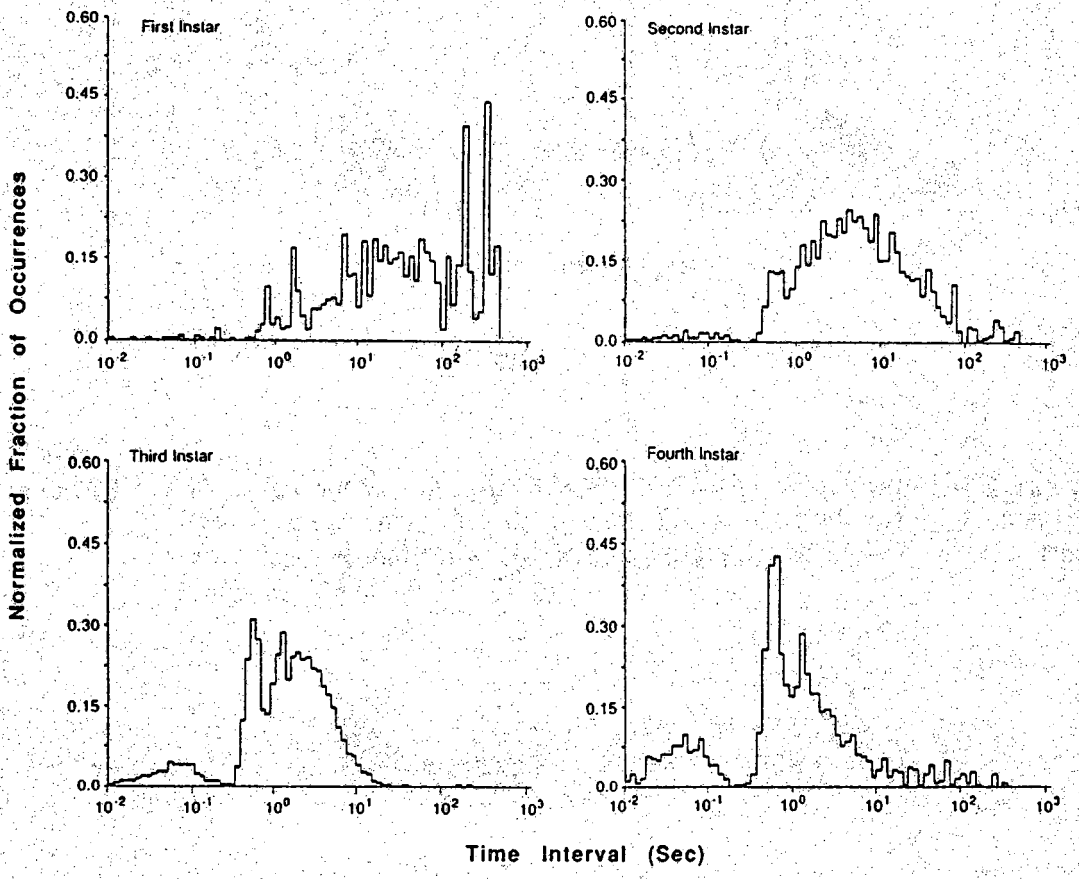


Figure 26. The normalized, standard vectors used to determine the stage of development of cowpea weevil larvae, which were generated from the typical time interval histograms of insects at the four stages of larval development.

typically generates approximately four times more events than the cowpea weevil, without significantly decreasing the length of the most common intervals. Although these differences in the interval distributions were hardly noticeable to the naked eye, they were enough that the age of the bean weevil could not be predicted accurately using the same typical histograms as were used for the cowpea weevil. With some further development, these differences could be used in a scheme to identify the species of insect present.

CHAPTER 5

CONCLUSIONS

These experiments have shown that one can determine if a cowpea weevil or bean weevil infestation is present by detecting the ultrasonic emissions associated with the feeding activity of the insects. Based on this conclusion, one would expect that any insect that feeds on dry plant material could be detected by monitoring its ultrasonic emissions. Thus far some other proven applications include the detection of the lessor grain borer feeding in wheat, the angoumois grain moth feeding in wheat, the rice weevil feeding in corn, and the subterranean termite feeding in soft pine [15].

The fact that the frequency spectra of the signals received from the cowpea weevil and bean weevil were more closely correlated with the species of seed housing the insect than the species of insect indicated that the received signal was actually the response of the seed to an impulsive event. Similarly, any insect which feeds on grain by fracturing the rigid substrate would be expected to generate a frequency spectrum corresponding to the impulse response of the seed housing the insect. Thus, given the species of seed in a particular storage unit, one can automatically know which frequency band to monitor for the optimum detection of insects. Another possible, though as of yet untested, application of this result is that the species of seed being monitored could be identified by the frequency spectrum generated by insects housed in the grain. Whether the latter application has any value has not yet been established.

The stage of development of cowpea weevils can be accurately determined using the testing procedure and the distribution of time intervals between feeding events, as was described in Chapter Four. Once one knows the stage of development of the cowpea weevil, the size of the infestation can be determined using the linear relationship between the number of events detected and the number of insects present. From this information, one can predict the amount of grain an infestation will consume.

Although these tests were conducted by placing a single bean against the transducer, results indicate that ultrasonic insect detection will be practical on

a larger scale. A system similar to that described in Chapter Three, except with a 40 kHz narrow band filter at the input has been able to detect one insect hidden in a container of 100 seeds, [18]. With moderate alterations to this system, even better results are expected.

Extending the technique derived in these experiments to a more practical level would be relatively simple. Random samples of seeds could be selected from a large volume of stored grain in the same way samples are taken for the conventional means of visual inspection. A single person could then ultrasonically inspect literally thousands of seeds in a short period of time, which represents a major improvement over the conventional method. With a little more development, however, the system could be automated even further by developing a series of probes which could be lowered into the grain elevator, which would then sample the grain at specified locations. Then the entire volume of stored grain could be monitored continuously.

The benefits of such a system would greatly outweigh the initial costs, by reducing simultaneously losses inflicted by insects, costs spent on pesticides, and concerns regarding the overuse of pesticides. Once an infestation has been detected and quantified, this information can be used to determine the amount of damage a given infestation could achieve. From this information, one can make an educated decision on which option would be more economical: fumigating the insects to halt further damage, or to avoid purchasing and applying pesticides to fumigate insects which are at a relatively harmless stage of development.

LIST OF REFERENCES

LIST OF REFERENCES

[1] Singh, S. R. and K. O. Rachie. *Cowpea Research, Production and Utilization,* pp. 230. New York: John Wiley & Sons, 1985.

[2] Shade, R. E. Purdue Associate Professor of Entomology, May 9, 1989, Personal Communication.

[3] Mentzer, P. E. Purdue Entomology Technician, May 10, 1989, Personal Communication

[4] Richardson, E. G. *Sound - A Physical Text-Book,* pp. 3. London: Edward Arnold & Co., 1940

[5] Weast, R. C., ed. *Handbook of Chemistry and Physics,* pp. E-41. Cleveland, OH: The Chemical and Rubber Co., 1970

[6] Lewis, M. J. *Physical Properties of Foods and Food Processing Systems,* pp. 146. Deerfield Beach, FL: VCH Publishers, 1987

[7] Blevins, R. D. *Formulas for Natural Frequency and Mode Shape,* pp. 233-334. New York, NY: Van Nostrand Reinhold Company, 1979

[8] Morse, P. M. *Vibration and Sound,* pp. 390. New York, NY: McGraw-Hill Book Company, Inc., 1948

[9] Massa Products Corporation. *Models E-152/40, E-152/75 Broadbeam Ultrasonic Tranducer, Preliminary Data sheet.* Hingham, MA: Massa Products Corporation.

[10] Industrial Quality, Inc. *New Product Bulletin: IQI Model 501 Dynamic Surface Displacement Transducer.* Gaithersburg, MD: Industrial Quality, Inc.

[11] Shade, R. E. Purdue Associate Professor of Entomology, May 5, 1989, Personal Communication.

[12] Klaassen, R. E. and E. S. Furgason. "Characterization of Ultrasonic Signals Generated by Concealed Insects." In *IEEE 1988 Ultrasonics Symposium Proceedings* ed. B. R. McAvoy, pp. 923-927. New York: Institute of Electrical and Electronic Engineers, 1988.

[13] Shade, R. E., E. S. Furgason, and L. L. Murdock. "Ultrasonic Insect Detector." United States Patent Number 4,809,554 March 7, 1989.

[14] Stark, H., and F. B. Tuteur. *Modern Electrical Communications Theory and Systems* pp. 438. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1979

[15] Furgason, E. S., R. E. Shade, and L. L. Murdock. "A Detector for Hidden Insect Infestations." Poster Presentation for Indiana CST, Purdue University. March 1988.

[16] Murdock, L. L. Purdue Professor of Entomology, June 15, 1989, Personal Communication via E. S. Furgason.

[17] Franks, L. E. *Signal Theory,* Revised ed. pp. 21. Stroudsburg, PA: Dowden & Culver, Inc., 1981

[18] Shade, R. E. Purdue Associate Professor of Entomology, May, 1988, Personal Communication.

APPENDICES

Appendix A: Transducer Specification Sheets

The following are photocopies of the manufacturer's original specification sheets for the transducers used for the experiments described in this thesis. The first transducer described was manufactured by Massa Products Corporation. This is the narrow band, highly sensitive air transducer, which was used to detect the signals from concealed insects for extended periods of time. The second transducer was manufactured by Industrial Quality Inc. This is the wide band transducer which was used to measure the spectral properties of sound emitted by concealed insects.

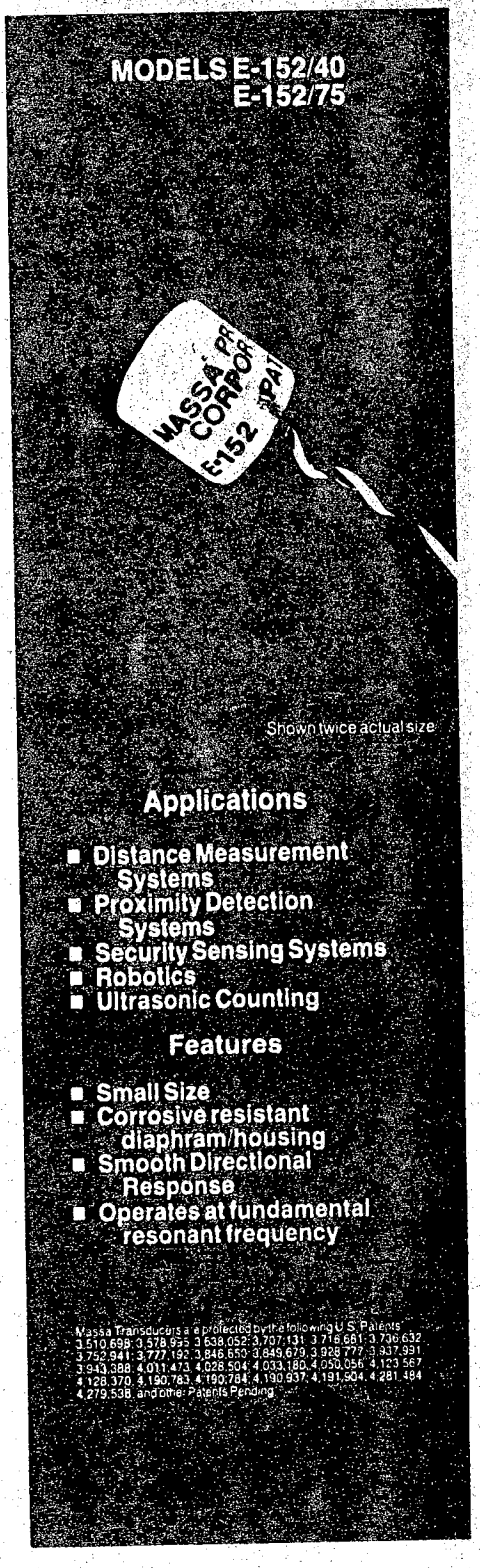
A.1 Massa Products Corporation

Massa
Products
Corporation

280 Lincoln Street, Hingham, Massachusetts 02043
Tel: (617) 749-4800 Twx: 710-348-6932

MODELS E-152/40
E-152/75
BROAD BEAM ULTRASONIC TRANSDUCER

preliminary data sheet



Description

E-152/40

The Massa Model E-152/40 is a miniature air ultrasonic transducer having many applications in short range sensing and remote control where non-contact is desired. The transducer operates at 40 kHz, its fundamental resonant frequency, thereby producing a relatively broad directional response, free of minor lobes. The housing and diaphram are one piece and made from stainless steel to provide high resistance to corrosive atmospheres. Each transducer is provided with 2 feet of twisted pair cable potted at in the back of the housing. Other lengths of cable or different terminations are available on special order. An external horn may be attached to reduce the beam angle for highly directional applications and maximum range.

E-152/75

The Massa Model E-152/75 is physically the same as the E-152/40 but operates at 75kHz. Operation at 75 kHz permits better resolution and performance in short range applications.

Massa Products Corporation is a leading designer and manufacturer of a wide variety of electroacoustic transducers and systems for use in air and underwater, with over 35 years of specialized experience in this field.

Models E-152/40 E-152/75

Specifications

	E-152/40	E-152/75
Frequency at	40 kHz	75 kHz
Receiving Sensitivity	±2 kHz	±2 kHz
Bandwidth		
Tuned	14 kHz	20 kHz
Untuned	1 kHz	1 kHz
Transmitting Sensitivity (dB vs 1 μbar per volt at 1 foot untuned)	110	110
Receiving Sensitivity (dB vs 1 volt/μbar untuned)	-57	-62
Rated Power	10mW	10mW
Nominal Impedence at minimum resonance	1000Ω	1000Ω
Total Beam Angle (-3 dB) Conical	75°	60°
Operating Temperature	0-70° C	0-70° C
Humidity	0-90%	Non-condensing
Weight	6 grams	6 grams

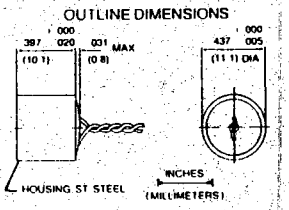
All specifications typical at 22°C and barometric pressure of 751mm of mercury and subject to change without notice.

Massa Products Corporation

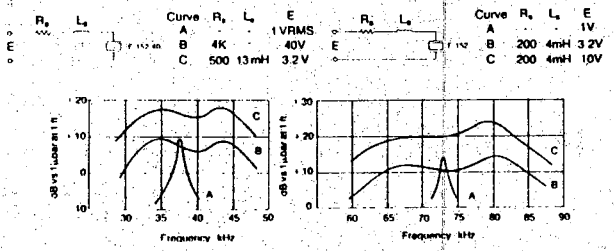
280 Lincoln Street
Hingham, Massachusetts 02043

Tel. (617) 749-4800
Twx. 710-348-6932

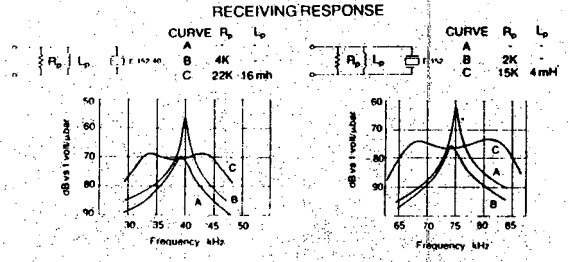
OUTLINE DIMENSIONS



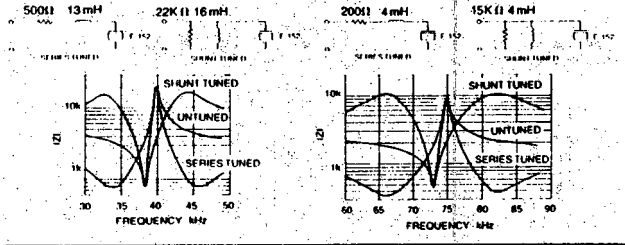
TRANSMITTING RESPONSE



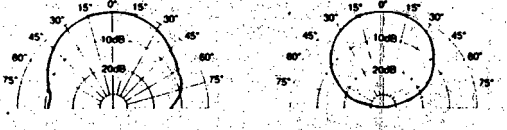
RECEIVING RESPONSE



IMPEDANCE



DIRECTIONAL RESPONSE



Represented By:

Printed in USA. 03-10-01-5M

A.2 Industrial Quality Inc.

INDUSTRIAL
QUALITY
INC

NEW PRODUCT BULLETIN

IQI Model 501 Dynamic Surface Displacement Transducer
(with matching preamplifier (unity gain) and shield)

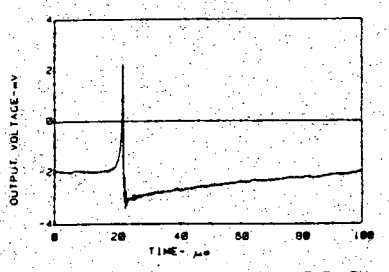
FOR HIGH FIDELITY ACOUSTIC EMISSION (AE) AND ULTRASONIC SIGNAL DETECTION

Model 501 Transducer being placed in shield/amplifier housing (a top view of the conical transducer element and backing is at the right.)

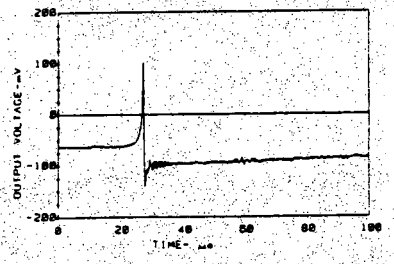
The Model 501 Transducer is a new, high sensitivity, flat response transducer that provides faithful measurement of minute normal surface displacements. The sensitivity is comparable to that of a normally used piezoelectric transducer. However, the Model 501 Transducer offers the exceptional feature of very flat frequency response over the range 50kHz to 1MHz. The frequency response begins to approach that of a capacitive transducer (see voltage/time response curves). The new Model 501 Transducer provides much higher sensitivity than a capacitive transducer and is more versatile in terms of object surface condition requirements for transducer placement and operation.

APPLICATIONS: AE monitoring of structural components.
Comparison calibration (as secondary standard) for AE or ultrasonic transducers.
Calibration of complete AE measurement system.
High fidelity ultrasonic detection in solids.
Calibration of complete ultrasonic spectroscopy system.

RESPONSE: Amplitude response flat within ±3dB, 50kHz to 1MHz.
Displacement sensitivity, 2×10^{8} V/m, nominal.



Voltage/Time response of NBS Capacitive, Standard Transducer for a step force event (breaking a glass capillary on a large steel block).



Voltage/Time response for the conical, piezoelectric transducer configuration used in the IQI 501 Transducer, for a similar step force event.

SPECIFICATIONS:	Transducer Head	Shield, Cover, Preamplifier
Dimensions	Cylindrical 1 ¾in (4.4cm) dia. 1 ⅛in (3.2cm) high	Cylindrical 6in. (15.2cm) dia. 2 ⅞in (7.3cm) high
Contact size	0.060in (1.5mm)	—
Weight	10oz (283g)	25oz (708g)
Construction	Brass, piezoceramic, plastic	aluminum, electronic circuit
Electrical	9 volt battery, Type NEDA 1604A Output Impedance: 50 ohms, BNC Connector Maximum Output Voltage: ±2 volts, peak to peak.	

The Model 501 Transducer is furnished with a shield and a matched preamplifier. The preamplifier has a unity gain (approximately) and provides a low output impedance (50 ohms) that permits the use of cables up to 50ft (about 15m) long, as needed; performance is limited by the cable only to the extent of the intrinsic attenuation of the cable. The use of battery power and the shield minimize the possibilities of electrically induced interference.

New concepts of transducer design have produced a device that is free of any significant resonances in the working range. The contact area is small (0.060in, 1.5mm); this gives freedom from the aperture effect and its attendant nulls and loss of high frequencies. The wear plate and other resonant structures have been eliminated. The conical shape of the piezoceramic element intimately coupled to an impedance-matched backing of extended physical size effectively eliminates resonances of the element itself. The large size and lossy character of the backing minimize coherent reflections back into the element. Extensions of the backing in the radial direction as well as in the axial direction result in an improved mechanical impedance match between the element and the backing. The combined effect of all these design features is a transducer that faithfully reproduces displacement waveforms on the surface of a structure.

REFERENCES:

Improved Piezoelectric Transducer for Acoustic Emission Signal Reception, T. Proctor, Abstract KK-4, J. Acoust. Soc. Am., Vol. 68, Suppl. 1 (Fall, 1980).

An Improved Piezoelectric Acoustic Emission Transducer, T. Proctor, J. Acoust. Soc. Am., 1982.

To place orders or to obtain further information

Contact: Industrial Quality, Inc.
P.O. Box 2397
Gaithersburg, MD 20879-0397
USA
Telephone: 301-948-0332

Appendix B: Computer Programs

The following programs were used to acquire and analyze the signals generated by concealed insects. The first program listed, PEAKTIME.BAS, was used to store the raw signals, These signals were detected using the second program, PT.ASM, which gathered the data by monitoring an analog to digital converter, and saving the peak voltages. The purpose of the third program, PK.BAS, was to convert the raw data stored by PEAKTIME.BAS into real numbers which could be easily interpreted. The fourth program, PROC5G.BAS, was a procedure which maximized the differences between signals recorded from insects at different stages of development. This program used the results from PK.BAS to generate 80 dimensional real vectors describing the time intervals between successive feeding events. Finally, PROJECTN.BAS was the program which examined the vectors created by PROC5G.BAS and identified the stage of development of the concealed insect.

Program Page

B.1 PEAKTIME.BAS 65
B.2 PT.ASM 66
B.3 PK.BAS 71
B.4 PROC5G.BAS 74
B.5 PROJECTN.BAS 79

B.1 Program PEAKTIME.BAS

```
1000 REM  Program: PEAKTIME.BAS
1001 REM  Calls PT.ASM subroutine
1002 REM  By Rich Klaassen  9/88   Language: BASIC
1003 REM  Program to input data from a/d board to file.
1004 REM  Samples continuously at 25 kHz, for length of
1005 REM  time specified by user.  Integer Data is stored
1006 REM  as A/D magnitude output, and time, represented by
1007 REM  number of cycles decremented, with timing marks
1008 REM  placed every 2.6 seconds (2^16 decrements).  Data
1009 REM  can be converted to real time using PK.BAS program.
1030 REM
1040 DIM dpk%(16000)
1050 input "How many minutes of data? ",a
1052 a%=int(a*23+.5)
1054 if a%<1 then a%=1
1060 print "Press any key to begin taking data."
1070 if inkey$="" then 1070
1075 print "Sampling data--please do not disturb"
1080 CALL pt(a%,dpk%(0))
1085 sound 2000,3
1087 if inkey$<>"" then 1087
1090 INPUT "File name? ",f$
1100 if f$="n" then 1240
1110 OPEN "O",#1,f$
1150 goto 1210
1160 if dpk%(i)+dpk%(i+1)=0 then 1240
1210 print #1,dpk%(i),dpk%(i+1)
1220 i=i+2
1230 goto 1160
1240 CLOSE #1
1245 stop
1250 end
```

B.2 Program PT.ASM

```
;
;
TITLE   SPECIAL ADC SAMPLING PROGRAM                (PT.ASM)
COMMENT *
        This program drives the TECMAR a/d module located
        at I/O address 1808 decimal. Its special purpose is to
        sample insects' sounds for 15 minutes at 25 kHz, saving
        data corresponding to peak magnitudes and time delays
        between them.  *
;
;
;       Equates used locally.
;
;
FCB_PTR     EQU05CH                 ;Pointer to File Control Block
ADDR    EQU1808
;
;
;       Macro for I/O output to timer and A/D board.
;
;
OPDMACRO  VAL,IOP
        MOV     AL,VAL
        MOV     DX,IOP
        OUT     DX,AL
        ENDM
;
;
;       Storage segment for sampled data.
;
;
STORE   SEGMENT PARA PUBLIC 'CODE'
```

```
STORE   ENDS
;
;
;       Current code segment labeled 'CODE' for linker.
;
;
PT_CODE     SEGMENT     PARA PUBLIC 'CODE'
        ASSUME CS:PT_CODE
        PUBLIC  PT
PT  PROC    FAR
        JMP PSTART
;
;
;       Local variable storage.
;
;
PEAK            DW  0           ;reserve space for input peak
THRESH          DW      2       ;trigger threshold
PEAK1           DB  0           ;flag to mark if peak has been found
;                               since last dip below THRESH.
VALUE           DB  0           ;Storage for low byte
NUM_LOOPS DW  0             ;Number of loops for 15 min. of data
;                           @ 25 kHz sampling rate.
;
;       Program start
;
;-------------------------------------------------------------
;
;       On entry: SP+6          beginning of array descriptor
;
;-------------------------------------------------------------
;
;
PSTART:     PUSH    BP              ;Save BP
        MOV     BP,SP               ;Save SP
        PUSH    ES
        MOV     SI,[BP]+8
        MOV     AX,[SI]
```

```
        MOV     NUM_LOOPS,AX
        MOV     SI,[BP]+6
;
;
;       Load CX with loop value
;
        MOV     CX,0
;
;
;       Setup board for continuous operation at 25 kHz.
;
;NORM:
        CLI                     ;Disable interrupts
        OPD     128,ADDR+4              ;Control byte
        OPD     23,ADDR+9               ;master mode select
        OPD     0,ADDR+8                ;1 MHz clock
        OPD128,ADDR+8           ;bcd divide
        OPD     5,ADDR+9        ;counter 5
        OPD49,ADDR+8            ;repetitive count
        OPD11,ADDR+8
        OPD58,ADDR+8            ;counts on 5 before TC
        OPD0,ADDR+8             ;
        OPD112,ADDR+9           ;load 5 and arm for counting
        OPD0,ADDR+5             ;select channel 0
        OPD132,ADDR+4           ;external start conversion enab
        MOV     DX,ADDR+5
        IN      AL,DX           ;reset status byte
        INC DX
        IN      AL,DX
;       decrement with LOOP instruction.
;
ADCV:   MOV     DX,ADDR+4       ;Status register address
STAT:   IN      AL,DX           ;Get status byte
        AND     AL,80H          ;Conversion when bit 7 goes high
        JZ      STAT            ;If bit 7 not set go back
        IN      AL,DX
        AND     AL,40H          ;test for overrun
        JNZ FINISH              ;if overrun--quit
```

```
        INC DX
        IN   AL,DX
        MOV     VALUE,AL
        INC DX
        IN     AL,DX              ;get hi byte
        MOV     AH,AL
        MOV     AL,VALUE
        CMP     AX,THRESH          ;is input below threshold?
        JL   RPEAK                 ;yes-check peak flag, save data
        CMP     AX,PEAK                    ;no-is input above prev. peak?
        JL   NEXT                  ;no-get next data
NPEAK:  MOV     PEAK,AX                    ;yes-save new peak and continue
        MOV     PEAK1,1            ;set peak flag
        JMP NEXT                   ;next data
RPEAK:  CMP     PEAK1,0            ;has peak occurred since last save?
        JZ   NEXT                  ;no-get next data
        MOV     AX,PEAK                    ;yes-restore peak to save
        MOV     [SI],AL            ;Store lo byte
        INC SI                ;Increment to next location
        MOV     [SI],AH            ;Store hi byte
        INC SI
        MOV     [SI],CL            ;save timing info
        INC SI
        MOV     [SI],CH
        INC SI
        MOV     PEAK1,0
        MOV     AX,THRESH
        ADDAX,10                   ;set next peak above THRESH jitter
        MOV     PEAK,AX
NEXT:   LOOP    ADCV               ;Go back if not done
;
;
        INC SI                ;mark loop, start again.
        INC SI
        MOV     AX,NUM_LOOPS
        MOV     [SI],AL
        INC SI
        MOV     [SI],AH
```

```
        INC SI
        DEC NUM_LOOPS
        JNZ ADCV
FINISH: STI                     ;Restore interrupts
;
;
        POP ES
        POP BP                  ;Restore registers
        RET 4                   ;return to basic-nothing passed
                                ;nothing lost
PT      ENDP
PT_CODE ENDS
        END
```

B.3 Program PK.BAS

```
1000 REM  Program:  PK.BAS        08/28/88
1010 REM  By Rich Klaassen   Language:  BASIC
1050 REM  program to take data from a peaktime file and
1100 REM  convert it to Magnitudes and times.  Saves data as
1200 REM  real numbers, times as the time in seconds at which
1201 REM  the event occurred, magnitudes as the digitized value
1202 REM  obtained from the A/D, scaled according to the users'
1203 REM  wishes.
1300 REM
1310 dim dpk%(8000)
1410 dim times(8000)
1500 INPUT "File name? ",f$
1505 REM
1510 REM derive filename for resulting data.
1520 REM
1600 f1$="imes
1610 REM
1620 REM get scaling factor
1630 REM
1650 input "Magnitude Multiplier? ",mult
1660 REM
1700 OPEN "I",#1,f$
1800 OPEN "O",#2,f1$
1900 i=0
2000 t=0
2050 if EOF(1) then 3650
2100 input #1,dpk%(i),d%
2200 if dpk%(i)<>0 then goto 2592
2202 REM
2204 REM if time marker encountered, increment base time.
2206 REM
2210 t=t+2.6087
2300 if d%=1 then 3650
```

```
2305 goto 2050
2590 rem
2592 rem Calculate time, unless magnitude is under .005 volts.
2594 rem
2600 rem  if dpk%(i)<20 then 2050
2700 times(i)=d%
2800 if times(i)>0 then times(i)=65536-times(i)
2900 if times(i)<0 then times(i)=-times(i)
3000 times(i)=times(i)/25000.+t
3400 i=i+1
3600 goto 2050
3650 times(i)=t
3660 dpk%(i)=0
4000 rem
4010 rem
4020 rem      Part II--check for noise.  if four or more events are
4030 rem      within 4/1000 second of neighboring events, in series,
4040 rem      assume it's noise.  Otherwise save in file.
4050 rem
4120 flag=0
4200 j=0
4210 if times(j+1)-times(j)>.004 then goto 4270
4215 if flag=1 then goto 4400
4220 if times(j+2)-times(j+1)>.004 then goto 4300
4230 if times(j+3)-times(j+2)>.004 then goto 4300
4240 if times(j+4)-times(j+3)>.004 then goto 4300
4246 if times(j+4)<.00002 then goto 4300
4250 flag=1
4260 goto 4400
4270 if flag=0 then 4300
4280 flag=0
4290 goto 4400
4300 m=dpk%(j)
4305 m=m*mult
4310 print #2,m,times(j)
4400 j=j+1
4500 if j<(i+1) then 4210
4700 CLOSE #1,#2
```

```
5800 stop
5900 end
```

B.4 Program PROC5G.BAS

```
1000 rem      Program: PROC5G.BAS      02/25/88
1010 rem      By Rich Klaassen   Language: Basic
1100 rem      Program to take data from a times file and count the
1105 rem      number of events corresponding to the time elapsed
1110 rem      between successive events, the logarithmic scale of
1120 rem      time is divided into 80 partitions.
1200 rem
1310 rem
1350 dim f4$(20)
1400 dim n(92)
1405 lg10=16/log(10)
1410 rem
1420 rem names of files to be operated on are stored in another file.
1430 rem get this file.
1440 rem
1450 input "Output file-list? ",f5$
1460 open "O",#5,f5$
1500 INPUT "Files' input files?  ",f3$
1510 open "I",#3,f3$
1537 input "Filename Extension? ",ex$
1540 if mid$(ex$,1,1)="." then ex$=mid$(ex$,2,3)
1548 ex$="."+mid$(ex$,1,3)
1550 on error goto 0
1551 input #3,f4$
1555 i$="u"
1560 rem  if at end of this directory, change directory
1570 if mid$(f4$,1,2)<>"cd" then goto 1600
1580 dir$=mid$(f4$,4,10)
1585 print dir$
1590 goto 1550
1600 lprint
1605 f4$=mid$(f4$,1,10)
1607 on error goto 0
```

```
1608 mid$(f4$,3,1)=i$
1610 f1$=dir$+f4$
1612 rem
1613 rem      open file to determine largest peak.
1614 rem
1620 on error goto 8000
1630 OPEN "I",#1,f1$
1640 on error goto 0
1650 print f1$
1660 rem
1661 rem      find largest peak in first two minutes of activity
1662 rem            (or in first 50 events, whichever is later.)
1663 oversh%=0
1664 ntot1%=0
1665 time=0
1666 largem=0
1667 largem1=0
1670 if EOF(1) then 1790
1680 input #1,m,t1
1686 if largem=0 then time=t1+360
1687 if ntot1%<150 then 1690
1688 if t1>time then 1790
1690 if m=0 then goto 1790
1695 ntot1%=ntot1%+1
1700 if m<largem then 1750
1710 largem1=largem
1720 largem=m
1730 if m>4094 then oversh%=oversh%+1
1740 goto 1670
1750 if m<largem1 then 1670
1760 largem1=m
1770 if m>4094 then oversh%=oversh%+1
1780 goto 1670
1790 rem
1791 rem      Invalid data if more than 1% overshoot.
1792 rem
1793 close #1
1794 oversh%=oversh%-1
1795 lprint f4$,ntot1%,oversh%,largem,largem1
```

```
1796 if oversh%<1 then 1800
1797 if ntot1%/oversh%<100 then 3670
1798 rem
1799 rem Adjust signal magnitude according to preamp.
1800 s=(largem1*.00035663)+.065240
1810 if i$="u" then s=s/36.5
1820 if i$="l" then s=s/610
1825 if i$="h" then s=s/2820
1830 if i$="m" then s=s/4150
1840 if i$="U" then s=s/36.5
1850 if i$="L" then s=s/610
1855 if i$="H" then s=s/2820
1860 if i$="M" then s=s/4150
1865 rem
1866 rem Set signal threshold
1870 s=s/3
1880 i$="u"
1885 d=36.5
1890 if s>.0024 then 1950
1900 i$="l"
1910 d=610
1930 if s>.0003 then 1950
1932 i$="h"
1933 d=2820
1934 if s>.00015 then 1950
1935 i$="m"
1940 d=4150
1950 thresh=((s*d)-.065240)/.00035663
1960 on error goto 0
1965 mid$(f4$,3,1)=i$
1970 f1$=dir$+f4$
1975 lprint f4$,thresh,
1980 on error goto 8200
1990 OPEN "I",#1,f1$
1995 on error goto 0
2050 for i=1 to 82
2060   n(i)=0
2070 next i
2080 ntot=0
```

```
2091 t1=0
2100 t0=t1
2130 if EOF(1) then 3100
2160 input #1,m,t1
2170 if m<thresh then 2130
2200 if m=0 then goto 3100
2220 rem  calculate sums
2240 dt1=t1-t0
2380 if dt1>0 then goto 2420
2400 dt1=.00008
2420 j%=int(log(dt1)*lg10)+35
2430 if j%<1 then j%=1
2440 if j%>82 then j%=82
2660  n(j%)=n(j%)+1
2670  ntot=ntot+1
3080 goto 2100
3090 rem
3100 rem  normalize with respect to total number of events for this data file.
3105 rem  only keep data between dt = .01 to 1000 sec.
3110 rem
3200 if ntot<1 then 3660
3210 f2$=mid$(f4$,1,8)+ex$
3230 if thresh>13 then print #5,f2$
3310 OPEN "O",#2,f2$
3410 for j%=3 to 82
3420  n(j%)=n(j%)/ntot
3428  print #2,n(j%)
3430 next j%
3500 lprint ntot,
3646 rem
3650 close #2
3660 CLOSE #1
3670 if EOF(3) then goto 3690
3680 goto 1550
3690 close #3,#5
3800 stop
8000 rem
8010 rem  Subroutine to correct for nonexistent files, to find largest peak
8020 rem
```

```
8025 rem
8030 if i$="m" then resume 3670
8040 if i$="M" then resume 3670
8042 if i$="h" then i$="M"
8044 if i$="H" then i$="M"
8050 if i$="l" then i$="H"
8060 if i$="L" then i$="H"
8070 if i$="u" then i$="L"
8080 if i$="U" then i$="L"
8100 resume 1607
8200 rem
8202 rem     Subroutine to correct for nonexistent files, to find a new
8204 rem     file which will still allow for threshold discrimination.
8206 rem
8225 rem
8230 if i$="m" then resume 3670
8240 if i$="M" then resume 3670
8242 if i$="h" then 8327
8244 if i$="H" then 8327
8250 if i$="l" then 8310
8260 if i$="L" then 8310
8270 rem     assume i$="u" or "U"
8280 i$="l"
8290 thresh=(610/36.5)*(thresh+182.93)-182.93
8295 if thresh>4095 then resume 3670
8300 goto 8330
8310 i$="h"
8320 thresh=(2820/610)*(thresh+182.93)-182.93
8325 if thresh>4095 then resume 3670
8326 goto 8330
8327 i$="m"
8328 thresh=(4150/2820)*(thresh+182.93)-182.93
8329 if thresh>4095 then resume 3670
8330 if i$="m" then 8340
8335 if thresh<13 then 8200
8340 resume 1960
9900 end
```

B.5 Program PROJECTN.BAS

```
1000 rem     Program:  PROJECTN.BAS  03/02/89  by Rich Klaassen
1100 rem
1200 rem     program to find the projection of data vectors onto
1300 rem     basis vectors calculated using PROC5G.BAS program.
1500 rem
1600 dim a(80,80), b(80), c(80), f2$(50), ave(80)
1610 input "File of vectors?",f2$
1700 input "File of filenames? ",f1$
1710 input "how many vectors? ",n%
1720 input "Average vector? ",f3$
1800 open "I",#1,f1$
1900 open "I",#2,f2$
1910 open "I",#3,f3$
1920 for i%=1 to 80
1930 input #3,ave(i%)
1940 next i%
2000 for i%=1 to 80
2020 for j%=1 to n%
2100   input #2,a(j%,i%)
2110 next j%
2200 next i%
2300 close #2
2400 input #1,f2$
2420 lprint f2$
2440 f2$=mid$(f2$,1,12)
2500 open "I",#2,f2$
2550 mag=0
2600 for i%=1 to 80
2700  input #2,b(i%)
2750  mag=mag+b(i%)^2
2800 next i%
2805 mag=sqr(mag)
2810 close #2
```

```
2820 for i%=1 to 80
2830  b(i%)=b(i%)/mag
2840 next i%
2850 mag=0
2860 for i%=1 to 80
2870  b(i%)=b(i%)-ave(i%)
2875  mag=mag+b(i%)^2
2880 next i%
2890 mag=sqr(mag)
2900 for i%=1 to n%
3000 for j%=1 to 80
3100   c(i%)=c(i%)+a(i%,j%)*b(j%)/mag
3200 next j%
3300 next i%
3415 n1=-1
3420 for i%=1 to n%
3425  if c(i%)<n1 then 3430
3426  n1=c(i%)
3427  n2%=i%
3430 next i%
3440 lprint n2%
3500 for i%=1 to n%
3600  c(i%)=0
3700 next i%
3800 if EOF(1) then 4000
3900 goto 2400
4000 close #1
4100 stop
5200 end
```