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**Portable high speed data acquisition system for ultrasound tissue
characterization**

by

Vincent J. Doerr

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CHAPTER 1. INTRODUCTION

This research involves the design and testing of an application specific portable ultrasound data collection system which can be used to discriminate between levels of intramuscular fat (marbling) in beef tissue. First, pertinent background information is reviewed, and the need for such a system is justified.

Ultrasound Background

Sound energy in the frequencies above the audible range is classified as ultrasound. There are a number of scientific and medical uses for ultrasound, including material fault detection and imaging. For imaging, pulse mode ultrasound is used. A burst of sound energy is sent out by an ultrasound transmitter, and an ultrasound receiver (often the same transducer) listens for echoes. The time delay between sending and receiving the signal, along with the velocity of sound for the medium, are used to calculate the distance between boundaries which caused reflections. Methods of using the reflections to produce an image include amplitude mode (A-mode), and brightness mode (B-mode) (Webster, 1978). A-mode imaging detects boundaries by applying a threshold function to the reflected signal. B-mode imaging produces a two-dimensional image by using a linear array of A-mode transducers. By applying a number of thresholds, a gray scale image can be produced.

In addition to imaging, pulse mode ultrasound has been used to characterize tissue using frequency domain analysis of reflected and backscattered signals (Gupta et al., 1982 and Kuk et al., 1986).

A boundary is any discontinuity where the media on either side of the discontinuity have different acoustic properties (specifically, acoustic impedance). The amount of the signal reflected and transmitted at a planar surface interface can be determined by the following equations (Wells, 1969 pp 11-12):

$$P_r/P_i = (Z_2 \cos a - Z_1 \cos b) / (Z_2 \cos a + Z_1 \cos b)$$

$$P_t/P_i = (2 Z_2 \cos a) / (Z_2 \cos a + Z_1 \cos b)$$

where

P_r/P_i is the pressure reflectivity of the interface

P_t/P_i is the pressure transmissivity of the interface

Z_1 is the acoustic impedance of medium 1

Z_2 is the acoustic impedance of medium 2

a is the angle of incidence of the wave

b is the angle of refraction of the wave

The acoustic impedance of muscle tissue is 1.70×10^{-5} (g / cm² sec), while it is 1.38×10^{-5} for fat tissue. Therefore, the power reflected at an ideal planar boundary of muscle and fat with normal incidence would be approximately 1% of the incident power (Wells, 1969, pp8-13).

Sound energy is dissipated (attenuated) by the medium through which it travels. Some of the sound energy is converted to heat as a result of the viscosity of the medium, and some of the sound energy is scattered (Felleppa and Yaremko, 1987). Therefore, the energy in the traveling sound pulse will decrease as a function of the distance traveled. Nonplanar boundaries will produce coherent reflections or cause scattering depending on the geometry of the interface and its size in relation to the wavelength of the sound wave (Gore and Leeman, 1977). Therefore, the energy

received by the transducer will be affected by both the boundary encountered, and the distance traveled.

The attenuation of soft tissue (for example, muscle or fat) is often approximated (Wells, 1969) to be 1 decibel per centimeter of tissue per megahertz (dB/cm/MHz), where the MHz term is the frequency of the sound.

Beef Grading Background

Beef coming from young cattle is classified at the time of slaughter as one of four quality grades including prime, choice, select, and standard. Figure 1.1 shows the USDA chart which is used to correlate the level of marbling of a beef carcass with the grade assigned to that carcass (USDA, 1965). The marbling score is determined by a subjective evaluation of the intramuscular fat of the longissimus dorsi muscle at the quartering point of the carcass between the 12th and 13th rib. This evaluation is done by trained USDA meat inspectors after the carcass has been cooled. Figure 1.2 shows pictures of the visible marbling used for comparison between the marbling score (Anselmo et al., 1987).

Ultrasound Beef Grading Background

The long term goal of research in ultrasonic beef grading is to produce a system which can be used to objectively determine the level of marbling in carcasses and in live animals. This method would remove the subjectivity from the grading process and could be used by cattle producers to select breeding stock, and to select the optimum time of slaughter (Brethour, 1990a).

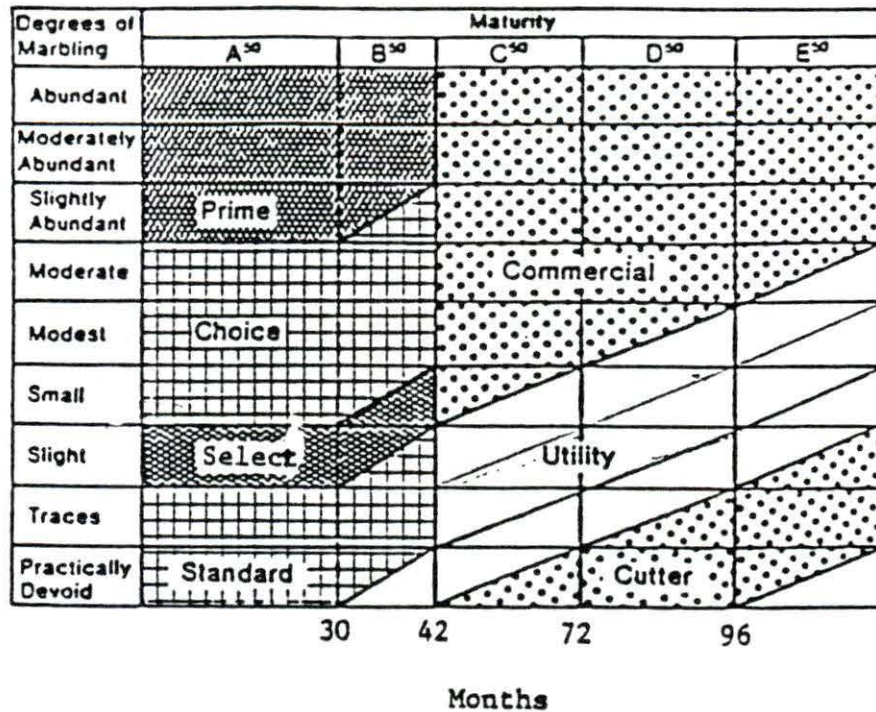


Figure 1.1 Chart used to determine carcass grade from the assigned marbling score (USDA, 1965)

B-mode imaging techniques have been employed by a number of researchers (Brethour, 1990b, Parks and Whittaker, 1990, Whittaker et al., 1990) to demonstrate a correlation between marbling score and processed images. However, B-mode imaging equipment usually employs techniques for eliminating specular reflections (as discussed in Gatenby et al, 1989). Since the specular reflections may contain information about the marbling content, B-mode imaging equipment may have limitations.

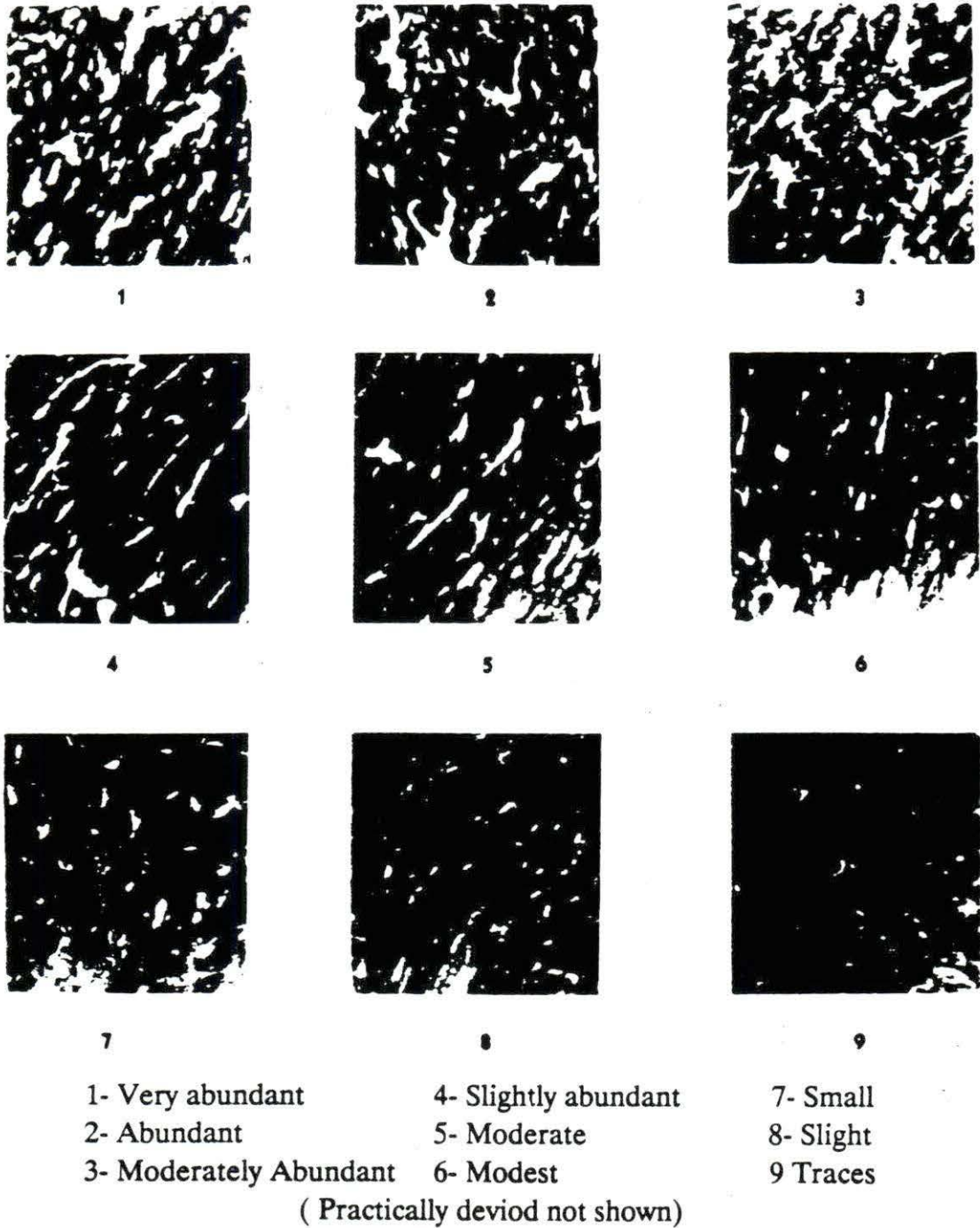


Figure 1.2 Visible marbling used by USDA Graders to determine the marbling score (Anselmo et al., 1987)

Whittaker et al. (1990) showed that a combination of spectral components (including center frequency, bandwidth, and spectral shift) of reflected ultrasound signals could be correlated with marbling score. Woods and Miles (1986) demonstrated a correlation between muscle concentration in beef tissue and attenuation and velocity of ultrasound. Haumschild and Carlson (1983) demonstrated that Bragg scattering could be used to correlate the beef grades in isolated samples of tissue extracted from the longissimus dorsi. Amin (1989) and Widyaatmadja (1991) demonstrated that attenuation measurements could be used to correlate with the fat content of longissimus dorsi samples. Chang (1991) demonstrated that reflected energy and spectral shift could be correlated with fat content in longissimus dorsi samples.

The above studies were performed on isolated meat samples in a laboratory setting with a large amount of laboratory equipment. If these techniques are to be applied in a beef grading system, a portable ultrasound data acquisition system is needed.

Statement of Purpose

The purpose of this work is to demonstrate the feasibility of a low cost portable ultrasound data collection system and to demonstrate signal processing techniques which can discriminate between marbling levels. Once signal processing techniques have proven to be adequate, this type of system could be modified into a marketable device.

CHAPTER 2. MATERIAL AND METHODS

A portable ultrasound data acquisition system for tissue characterization was designed and implemented. This system was used to acquire raw ultrasound data from beef carcasses within an hour of slaughter. These ultrasound signals were analyzed to discriminate between levels of intramuscular fat.

System Design

A microcontroller based high speed ultrasound data acquisition circuit board (DAB) was designed and built. This board was designed to communicate with a portable personal computer (PC). The communication involved down-loading commands from the PC to the DAB and up-loading a digitized ultrasound signal from the DAB to the PC. Figure 2.1 shows a block diagram of the resulting system.

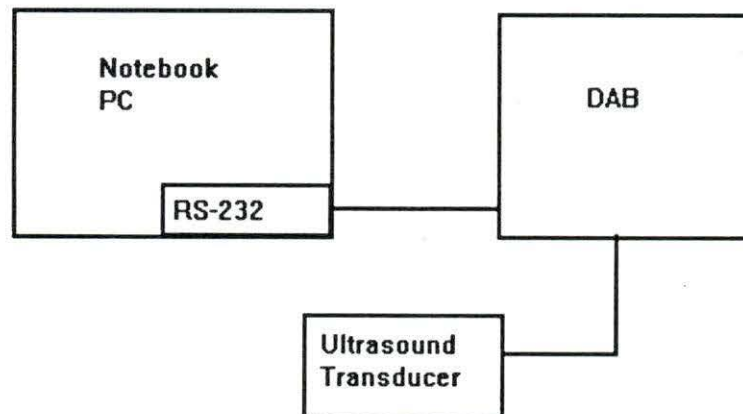


Figure 2.1 Complete data acquisition system

Data Acquisition Board Hardware Description

Figure 2.2 shows a block diagram of the DAB (see Appendix A for a complete schematic diagram of the DAB). The circuit consists of an ultrasound pulser, an ultrasound transducer, analog signal conditioning circuitry, a flash analog to digital converter (ADC), a high speed data buffer, a serial interface, and power supplies. The circuit also includes an embedded microcontroller which coordinates the actions of all the other circuits.

The ultrasound transducer and pulser The ultrasound transducer used in this system is an inductively tuned PZT transducer manufactured by Renco¹ (serial number 3701), with a center frequency of 2.2 MHz. This transducer was used as a burst mode transmitter and as an echo receiver. For pulsing the transducer, a P-channel MOSFET (Q1) is used as a switch in series between a voltage source (+9 V) and a diode (D1) which connects to the transducer (Tr1). While the switch is closed, current flows through the tuning inductor of the transducer. When the switch is opened, the energy stored in the magnetic field of the inductor causes a large voltage spike across the piezoelectric transducer which then emits a burst of sound. Figure 2.3 shows the gate voltage of the FET at turn off time as well as the resulting voltage spike at the transducer. The MOSFET is driven by a decoder (74HC138) with a zener diode used for level shifting. The decoder is driven by the microcontroller.

¹ Renco Corporation, Minneapolis, MN USA

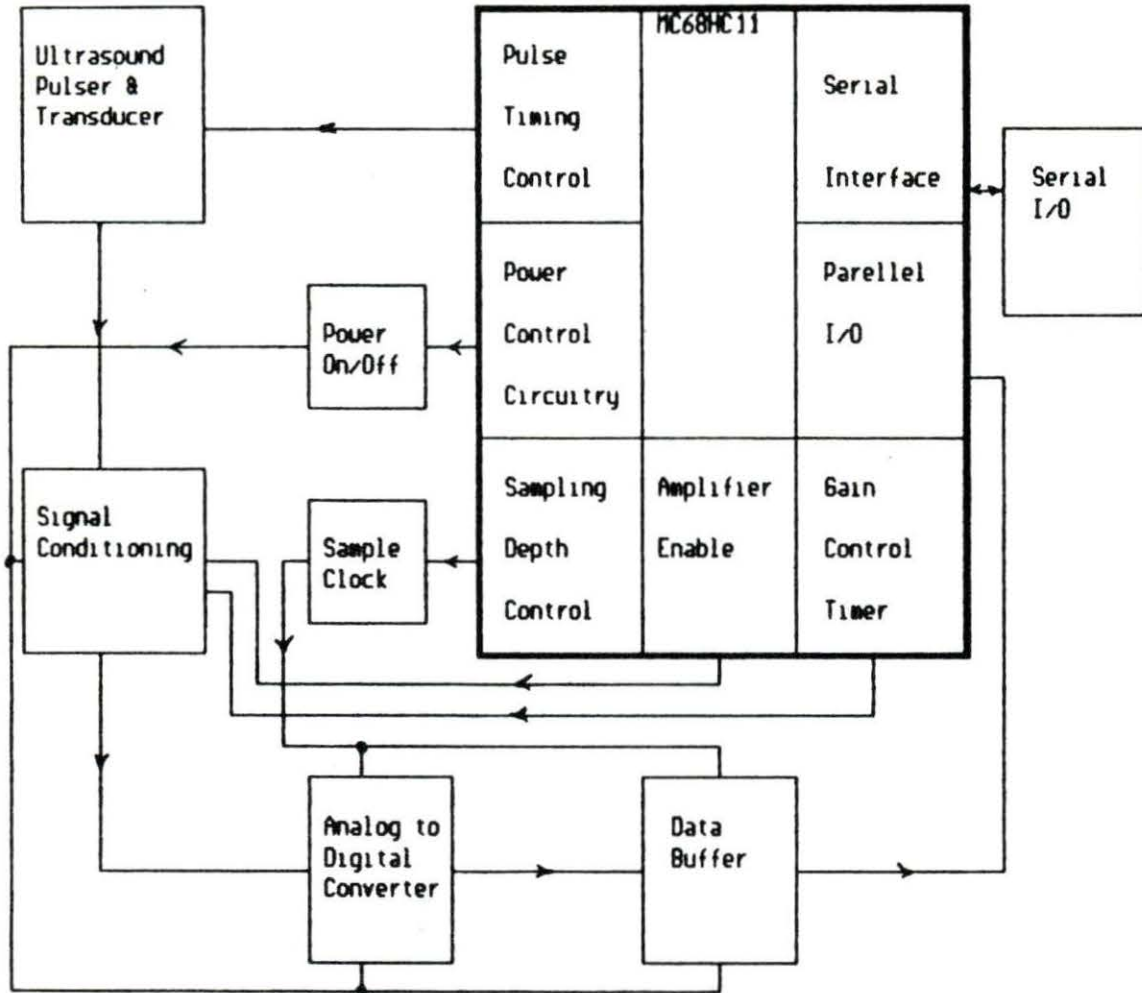


Figure 2.2 DAB block diagram

Signal Conditioning Circuitry The signal conditioning circuitry is designed to amplify the reflected echoes received by the ultrasound transducer and to bandlimit the received signal to the appropriate bandwidth. In addition, this circuitry shifts the voltage level to the appropriate range for the ADC (between 0 and -2 volts).

Amplification is accomplished in three stages. The first stage has a constant gain of 41 dB and is implemented using one amplifier of an AD600 (U6A), which is manufactured by Analog Devices². The second stage has a variable gain between 0 and 40 dB and is implemented using the second half of the AD600 (U6B). The third stage has a fixed gain of 15 dB and is implemented using an AD847 (U8). This stage also introduces a single pole low pass filter with a cut off frequency of 3.0 MHz, and adds a bias to produce an output voltage centered around -1 volt. Between the first and second stages is a single pole passive bandpass filter with cutoff frequencies at 500 kHz and 3.0 MHz. This filter has the dual

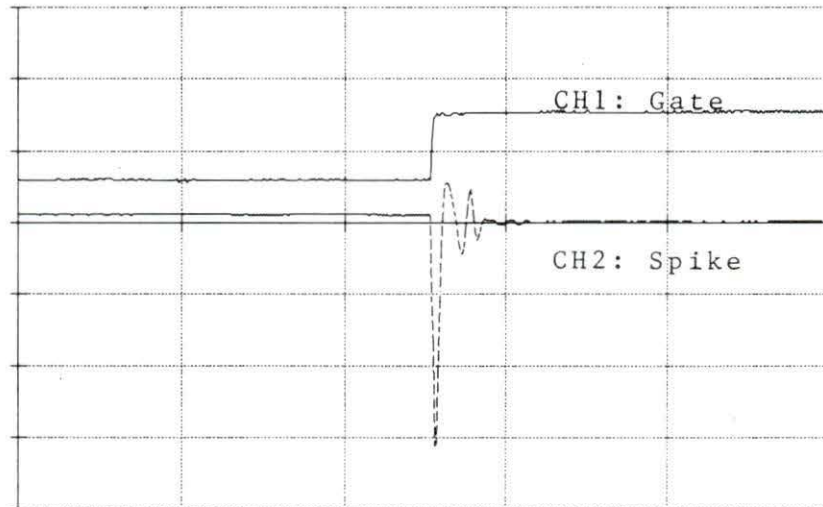


Figure 2.3 Pulser waveform at turnoff time (X-axis 5 usec/div): CH1 (top trace) MOSFET gate voltage (5 V/div), CH2 (lower trace) voltage spike across the transducer (5 V/div)

² Analog Devices, Norwood, MA USA

purpose of preventing offset voltage of the first stage from saturating later stages, and limits noise by bandlimiting the system. However, this filter introduces 6 dB of attenuation.

The second amplifier stage has been designed with a variable gain in order to compensate for the attenuation of ultrasound in tissue. The AD600 provides two inputs to control gain of the amplifier stage. A linear increase in voltage between these pins will cause a linear increase in the decibel gain of the amplifier. The variable gain of the second stage uses this feature and it is controlled by a time gain control (TGC) circuit. The TGC circuit is an integrator implemented using an OP-20 (U5) manufactured by PMI³. The integrator is biased at 2.5 volts and is used to integrate one of the timing signals from the microcontroller. By integrating a step voltage change, the TGC circuit produces a linear ramp. By using this ramp to drive the gain control of the AD600, the amplifier will have an increased gain over time. The time constant of the integrator was chosen to produce a linear ramp with a slope of 0.021 volts per microsecond (V/usec). This yields a time gain control of 2.6 dB per centimeter of tissue that the ultrasound travels through. Figure 2.4 shows the results of this gain compensation on a 2 MHz sine wave over a 25.6 usec time period.

Finally, in order to prevent the initial voltage spike (which stimulates the transducer) from saturating the amplifiers, the microcontroller disables the first amplifier stage during the pulsing of the transducer. In addition, diodes D3 and D4 prevent the voltage from exceeding the maximum allowable input voltage for the AD600.

³ Precision Monolithics Inc, Santa Clara, CA USA

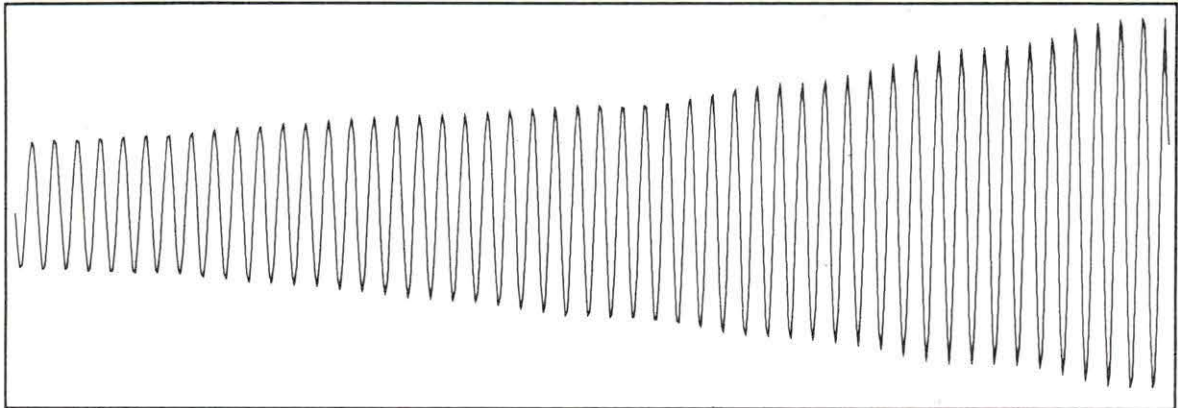


Figure 2.4 Time gain control compensation for a 2 MHz sine wave over 25.6 microseconds. The gain increased from 23 dB to 33 dB over this time period.

Analog to Digital Conversion Analog to digital conversion is accomplished using an eight-bit flash converter, AD9048 (U10), manufactured by Analog Devices². The clocking of this converter was accomplished using a 20 MHz CMOS clock oscillator (U9). The clock output was enabled using one of the timing signals from the microcontroller. This allows the microcontroller to select a window of the reflected ultrasound signal for processing. A low impedance reference voltage is generated using an error amplifier (U15) which drives the base of an emitter follower amplifier (Q2) (Analog Devices, 1989).

The high speed data buffer Since the microcontroller is not capable of operating at the 20 MHz rate of the ADC, the data has to be buffered. To accomplish this, a high speed first-in first-out serial memory (FIFO) is connected to

the output of the ADC. A DS2009 (U11), manufactured by Dallas Semiconductor⁴, was used because it met the required 50ns write time required for a 20 MHz sampling rate. This component has 512 bytes of memory. Since the output of this FIFO is at LS-TTL level, and the microcontroller requires HC input levels, a 74HCT540 (U12) was used to convert between the logic levels.

Power supplies All of the circuits are powered by two power supplies providing +5 volts and -5.2 volts. A 7805 (U14) voltage regulator is used to produce a regulated +5 volts from a +9 volt battery source. A 7905.2 (U13) voltage regulator is used to produce -5.2 volts from a -9 volt battery source. In order to conserve energy during idle times, power to some of the circuitry (signal conditioning, ADC, and the data buffer) is turned off by the microcontroller using FET switches Q3, Q4, and Q5.

The microcontroller The embedded microcontroller (Motorola⁵ MC68HC11A1, U1) controls the precise timing needed to synchronize the transducer pulser and the ultrasound signal sampling, as well as the critical timing of the signal conditioning. In addition, the microcontroller communicates with the high speed data buffer. Finally, the microcontroller has a serial interface which allows the DAB to communicate with an external computer. The microcontroller is wired to operate in bootload mode. This allowed for flexibility during the

⁴ Dallas Semiconductor, Dallas, TX USA

⁵ Motorola Semiconductor Products Inc, Phoenix, AZ USA

development of the microcontroller software, and eliminated the need for external memory.

Microcontroller Software Description

The microcontroller software consists of the following five functional blocks:

- 1) Initializing the microcontroller.
- 2) Receiving setup commands.
- 3) Cycling power.
- 4) Timing the transducer pulsing and data acquisition events.
- 5) Serially transmitting the ultrasound data.

Figure 2.5 shows a flow graph of this code. See Appendix B for a listing of the Motorola 68HC11 source code.

Initializing the microcontroller After the microcontroller is bootloaded, the microcontroller is initialized. First, a region of random access memory (RAM) is allocated as a stack. Next, serial communication with an external computer is set up and enabled. Finally, input/output (I/O) pins are programmed for the appropriate direction (either input or output) and output pins are set to appropriate initial logic levels.

Receiving setup commands Once the microcontroller is initialized, it is put into a wait state. In this state, the microcontroller waits for one of three serial commands from the external PC. If the ASCII code for a "D" is received, the code branches to a subroutine for setting up a delay. In this subroutine, a one byte delay number is serially received and stored. This delay number controls the timing

between the pulsing of the transducer and the start time for digitizing the reflected signal (using the microcontroller line labeled Acquire). This delay number allows the microcontroller (and therefore the user of the microcomputer) to control the depth of the sampling of the ultrasound signal. The actual delay time is equal to the delay number times 0.5 microseconds. This method allows for depth control between 0 and 127.5 microseconds. Assuming that sound travels approximately 1500 meters/second (m/sec) in tissue, the allowable depth control is 0 to 9.6 centimeter (cm), in steps of 0.375 cm.

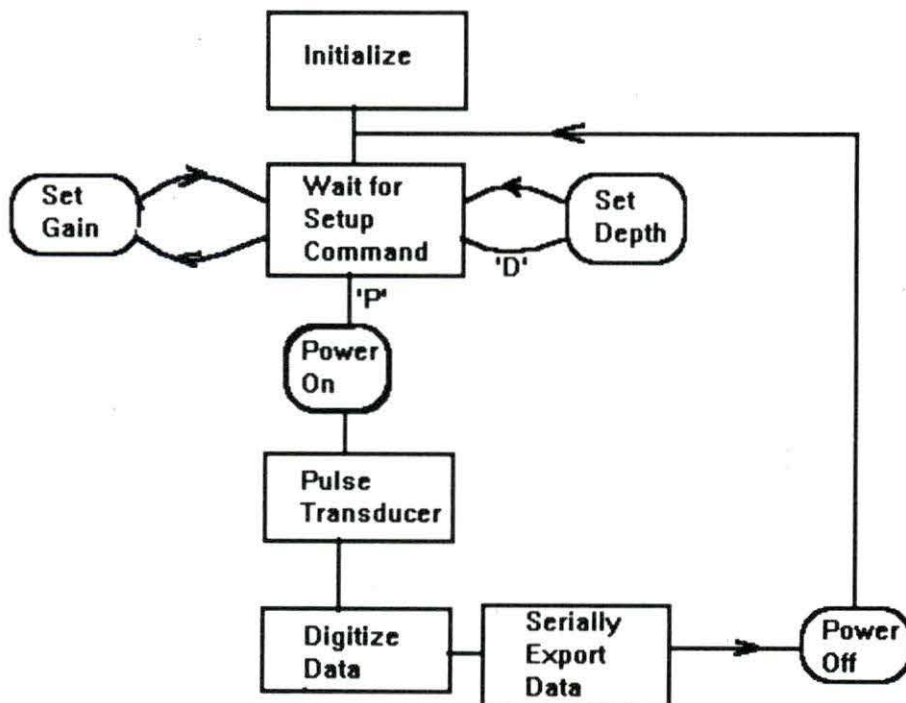


Figure 2.5 Microcontroller software flow diagram

During the receiver setup routine, if an ASCII code for a "P" is received, the microcontroller branches to a routine which turns on power, pulses the transducer, and digitizes a portion of the reflected signal.

The third possible setup command is to transmit a gain number. As the name implies, the gain number allows the microcontroller to vary the gain of the signal conditioning circuitry. With a 20 MHz sampling rate and a 512 byte FIFO, only 25.6 microseconds of data is stored. Since the TGC circuit generates a voltage ramp with a slope of 0.021 volts per microsecond, the maximum voltage change over 25.6 microseconds is 0.54 volts. However, the AD600 amplifier has a linear decibel gain control over a range of 1.25 volts. Therefore the gain number is used to shift the TGC ramp in time (relative to the data acquisition window) in order to allow the microcontroller (or the microcomputer user) to vary the amplifier gain.

Cycling power An output line of the microcontroller is used to activate the power switching transistors, which conserves power during idle times. Prior to removing power from unneeded circuits, the microcontroller sets all logic signals which go to these circuits to 0 volts.

Timing transducer pulsing and data acquisition events The microcontroller has five timing output pins. These pins can be programmed to set, reset, or toggle. The programmed action occurs when the system counter matches a register assigned to the appropriate timer. Using a bus cycle rate of 2 MHz, these timers can have as low as a 0.5 microsecond resolution. In the DAB, there are four events which require accurate timing control. These are the transducer pulsing, driving the

Acquire line (data acquisition windowing), driving the TGC circuit, and disabling the amplifier during pulsing. The fifth microcontroller timing output is used to drive the READ input of the FIFO after data acquisition is complete.

To control the four timing events, the main system counter is read and a setup time is added. Then all four events are setup to occur at an offset from this value. First, the TGC timer is setup to toggle high. Then, a minimum TGC setup time is added. This allows the integrator to get within the valid linear range for the AD600. Then, the gain term is added to allow for shifting the gain within the linear region. Then, this time is used to setup the data acquisition timer (Acquire). Figure 2.6 shows the TGC ramp and the Acquire timer output for a low gain setting and a high gain setting. This ramp shifting allows for programmable gain control using a gain term transmitted from the PC to the DAB.

Once the Acquire time is determined, the delay term is subtracted. This yields the time of the transducer pulsing, which is stored on the stack. As noted in the hardware description section, the transducer is pulsed by charging an inductor and then switching off the source. Therefore, the charging time is subtracted then the pulser timer is set to toggle low (which will start the charging of the inductor). Once the pulser timer toggles low, the pulse time is pulled from the stack and used to toggle the pulse high again (thus switching off the voltage source and pulsing the transducer). Finally, 7.5 microseconds is added to the pulse time and stored in the amplifier enable timer. Therefore, the amplifier will be enabled 7.5 microseconds after the transducer is pulsed. Figure 2.7 shows the pulser timer waveform and the amplifier enable waveform. Figure 2.8 shows all four timer outputs for one ultrasound pulsing event.

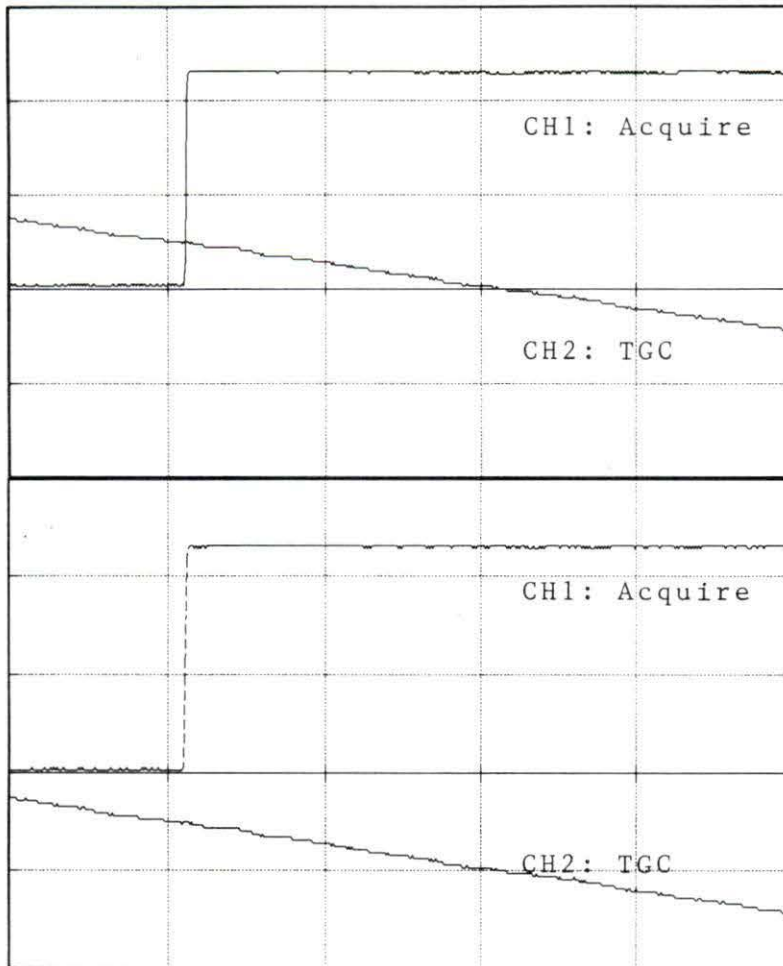


Figure 2.6 Demonstration of TGC ramp shifting (CH1: Acquire signal 2 V/div, CH2: TGC ramp, 0.5 V/div, X-axis is 10usec/div): a) data acquisition starts at a low gain, b) data acquisition starts at a high gain

Serially transmitting the ultrasound data Once the 512 point FIFO has been filled by the ADC, the microcontroller reads each datum point from the FIFO and then transmits it to the PC via the serial output port.

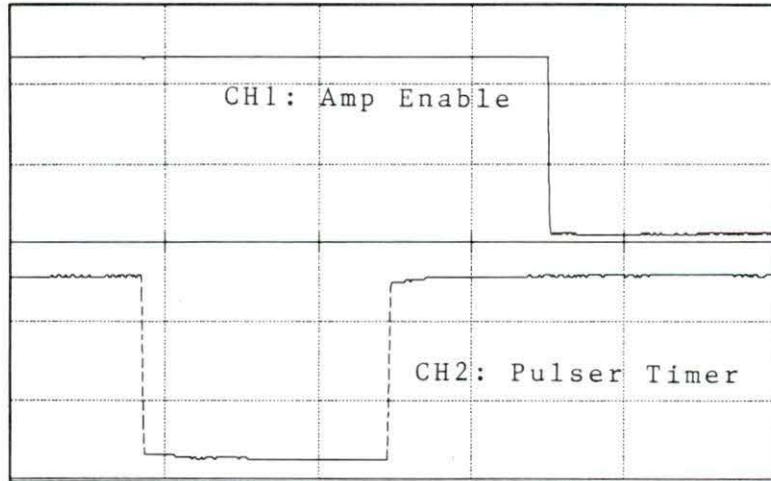


Figure 2.7 Pulser timer outputs and amplifier enable output (CH1: amp enable, 2 V/div, CH2: pulser timer, 2V/div, X-axis: 5 usec/div)

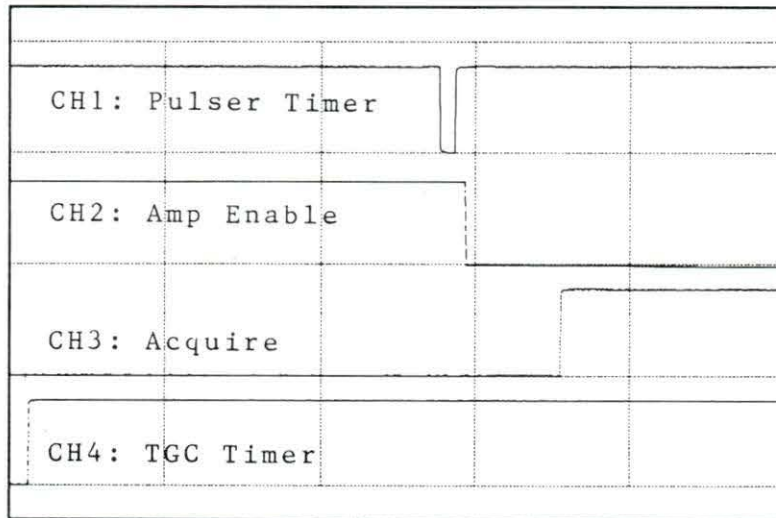


Figure 2.8 Microcontroller timer outputs: pulser (top signal), amplifier enable (second signal), Acquire (third signal), and TGC (bottom signal): X-axis 20 usec/div. All signals are 0 to 5 V signals (6 V/div)

PC Description

The PC used in ultrasound data collection was a Toshiba⁶ T1000SE notebook computer with a standard RS-232 port for serial communication with the DAB. For programming this computer, Microsoft Quick BASIC was used. Appendix C is a listing of this source code.

The PC code has seven functional blocks including:

- 1) Bootloading the DAB.
- 2) Setting the gain control variable.
- 3) Setting the depth control variable.
- 4) Pulsing a transducer.
- 5) Receiving the reflected ultrasound data.
- 6) Displaying this data.
- 7) Storing the data on a disk for later processing.

Bootloading the DAB The PC code starts by opening a file containing the assembled microcontroller code and converting this code to byte values. Then, the PC waits for the DAB to be powered up. When the DAB power has been applied, the PC transmits the controller code to the DAB via the serial port.

Setting the gain control After bootloading is complete the user is prompted for a gain setting, which is downloaded to the DAB. After each acquisition the user may change the gain setting if the need arises.

⁶ Toshiba, Tokyo, Japan

Setting the depth control The current PC code has 5 pre-programmed depth settings starting at 1 cm into the tissue with each following acquisition going 1.8 cm deeper than the previous one. This code could easily be modified for different experimental protocols.

Pulsing a transducer The ASCII code for a "P" is sent to the DAB to initiate the pulsing of a transducer.

Receiving the reflected ultrasound data Once the pulsing command has been issued, the PC waits for the DAB to transmit the digitized reflection.

Displaying the data In order to provide the user with a pictorial representation of the received data, the data is display graphically by drawing lines between the data samples.

Storing the data Once the data has been displayed, the user is asked if this data should be stored. If the user responds with a yes, then the user is requested to provide sample identification. Then the PC stores the raw data, along with the identification, as well as gain information, and depth information on a floppy disk. Once this is complete, the PC waits for the user to request the next sample be taken.

Carcass Data Collection Methods

Ultrasound data was collected at three meat packing plants. All ultrasound data was collected on warm carcasses within 1 hour of slaughter. Initially, all data

was collected from the dorsal side of the longissimus dorsi between the 12th and 13th ribs using water as a coupling agent between the transducer and the backfat. However, at two of the packing plants, automatic hide pullers were used. This resulted in irregular and inconsistent patterns of trapped air pockets in the backfat. Since the reflection coefficient for air is high, these air pockets lead to irregular and inconsistent data.

Experiments on data collection from the ventral side of the longissimus dorsi were much more consistent; however, the diaphragm blocked the normal grading site of the region between the 12th and 13th ribs. Therefore, all ventral data was taken in the region between the 10th and 11th ribs.

For each carcass, the DAB was used to acquire data at five different depths, starting at 1 cm into the tissue, then incrementing the depth by 1.8 cm with each subsequent depth. This resulted in ultrasound reflections from 1 cm into the tissue through 10.1 cm into the tissue.

CHAPTER 3 RESULTS AND DISCUSSION

This section presents the results of the designed system; then the limitations of this system are discussed. In addition, an analysis of data acquired in the field is presented. Finally, recommendations for future work are given.

System Results

To evaluate the system, the following characteristics were analyzed:

- 1) Impulse response.
- 2) TGC results.
- 3) Filter results.
- 4) Power requirements.
- 5) Cost requirements.

Following the above evaluation, the system's limitations are discussed.

Impulse Response

Figure 3.1 shows the impulse response of the ultrasound transducer. This signal was generated by digitizing the reflection generated by a small plastic sphere (0.4 cm radius) then zero padding the signal to extract the reflection from the initial surface. This was done with the TGC circuitry disconnected. Figure 3.2 shows the discrete Fourier transform (DFT) of the impulse response signal. To generate the DFT, a 512 point decimation in frequency, fast Fourier transform was used (as in Appendix D).

From these graphs, the center frequency of the transducer is 2.1 MHz, with a -12dB bandwidth of 1.4 MHz.

Time Gain Control Results

Figure 3.3 demonstrates the effectiveness of the TGC in compensating for tissue attenuation. Figure 3.3a shows the ultrasound reflection from a piece of the

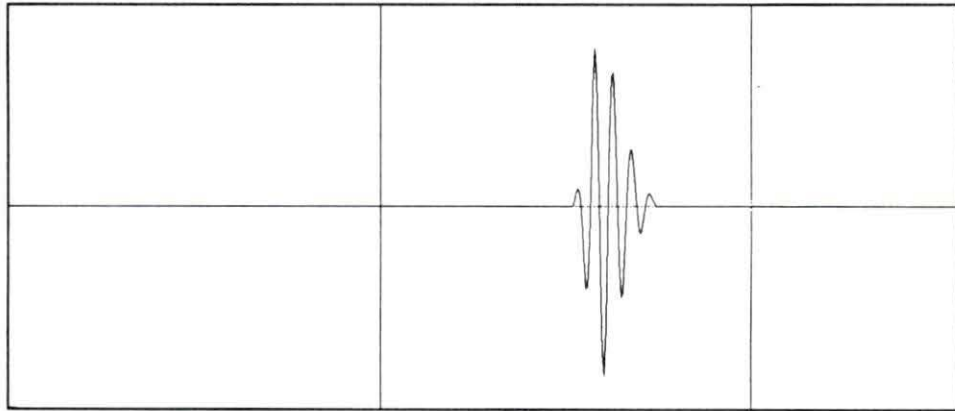


Figure 3.1 Transducer impulse response (10 usec/div, 1 V/div)

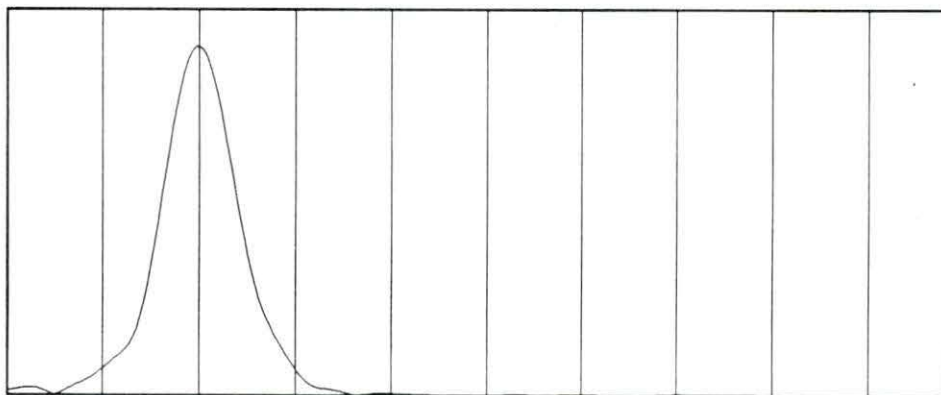


Figure 3.2 Frequency domain impulse response (1 MHz/div, arbitrary amplitude)

longissimus dorsi with the TGC connected. Figure 3.3b shows a signal from the same sample with the TGC disconnected. This demonstrates that signals deeper in the tissue can be resolved into more bits than would be possible without the gain compensation. This gain compensation could allow the assessment of the richness of the reflected ultrasound signal.

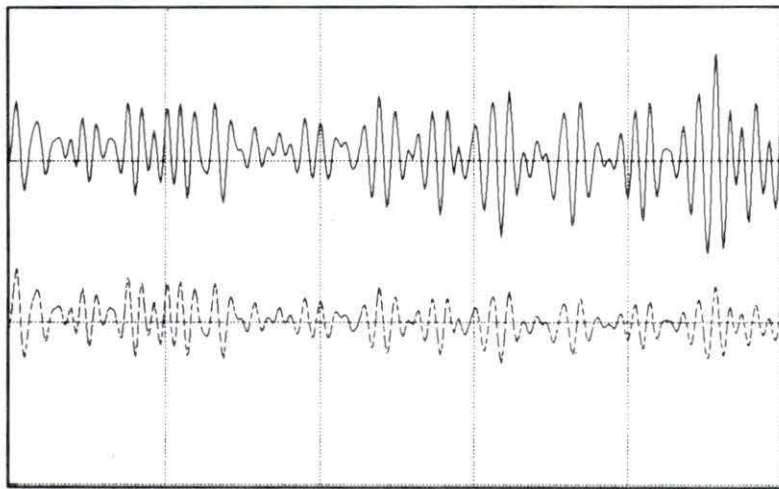


Figure 3.3 Demonstration of TGC effectiveness (X-axis 5 usec/div, amplitude 1 V/div at DAC): a) Ultrasound reflection from meat sample with TGC, b) Ultrasound reflection from the same meat sample without gain compensation

Filter results

Figure 3.4 shows a bode plot of the system. This plot was generated by providing a sine wave input and measuring the amplitude of the conditioned signal for a number of frequencies. The measured -3 dB low frequency is approximately 500 kHz with a roll

off of approximately -6 dB per octave. The measured -3 dB high frequency is approximately 2.5 MHz with a roll off of approximately -12 dB per octave. The analysis of the impulse response suggests that frequencies beyond 2.7 MHz may contain relevant spectral information; therefore, the low pass cut off frequency should be raised to at least 3 MHz for this transducer. However, for this experiment, the cutoff frequencies were fixed for all samples. Therefore, comparison of the spectral information of different samples can still be considered legitimate.

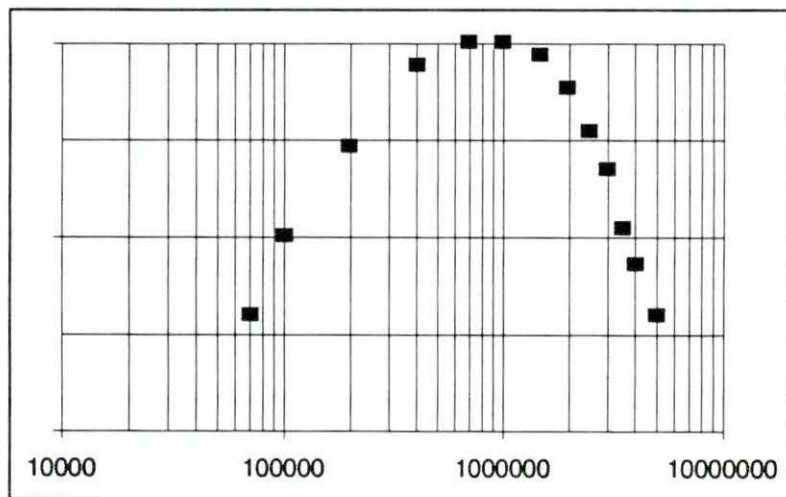


Figure 3.4 Bode plot generated using a constant magnitude sine wave input (X-axis: frequency in Hz, Y-axis: amplitude in dB with 5 dB/div scale)

Power requirements

During data acquisition, the DAB draws 118 milliamperes (mA) from the +9 V battery and 132 mA from the -9 V battery. During idle time, the DAB draws 25 mA from the +9 V battery and no current from the -9 V battery.

Cost requirements

Appendix F is a list of the materials required for the DAB, as well as an estimate of the cost for each item. These estimates are based on the assumption that components can be purchased in a moderate order size (100 at a time). The total estimated cost for the DAB hardware is \$200. Therefore, including the cost of a T100SE notebook computer, a portable ultrasound data acquisition system can be set up for under \$1000.

System limitations

Originally, the DAB was designed to accommodate an eight transducer array. This was accomplished by using the microcontroller to select which of the eight outputs of the 74HC138 (U4) would pulse low. These outputs would drive an array of eight transducers which were multiplexed using an analog 8-1 multiplexer 74HC4051. The output of this multiplexer would be fed into the signal conditioning circuitry. However, noise problems occurred in this circuit. The primary cause of this noise was a long path that current had to travel to get from the grounded side of the transducer to the ground plane of the amplifier circuitry. This noise was eliminated by connecting a single transducer directly across the input to the first amplifier stage and its ground plane.

A second problem encountered while developing the DAB was inadequate excitation of the ultrasound transducer. Initially, the regulated +5 V supply was used to charge the tuning inductor of the transducer; however, this did not produce enough ultrasound energy to penetrate much beyond the surface of the tissue. Using the +9 V battery instead of the +5 V produced a much greater sound pulse (voltage spike of 22 V vs 10 V). Using the +9 V to stimulate the transducer proved adequate for tissue

penetrating; however, the unregulated voltage was very sensitive to temperature and battery freshness.

Another problem encountered in the field was the difficulty of assuring consistent transducer coupling. Variations in coupling could greatly affect the amount of energy transmitted into and received from the tissue.

Data Analysis

The objective of collecting ultrasound signals is to determine the amount of intramuscular fat (marbling). The magnitude of the reflected signal is reviewed as a possible method for marbling discrimination. A second method looks for shifts in the center frequency and bandwidth in the spectrum of the reflected signals.

Time domain analysis

Figure 3.5 shows the A-mode reflections for two samples. Figure 3.5a shows a highly marbled sample (moderately abundant 60%), while 3.5b shows a lower marbled sample (slight 50%). From this figure, it appears that the richness of the reflected signal could be used for grade determination; however, the coupling problem and the unregulated stimulating voltage make statistical analysis impossible. In addition, there appeared to be a large degree of individual variability independent of grade.

Frequency domain analysis

The Microsoft Quick BASIC code listed in Appendix D was used to generate the spectrum of reflected signals as well as the peak frequency and -12 dB bandlimits. In

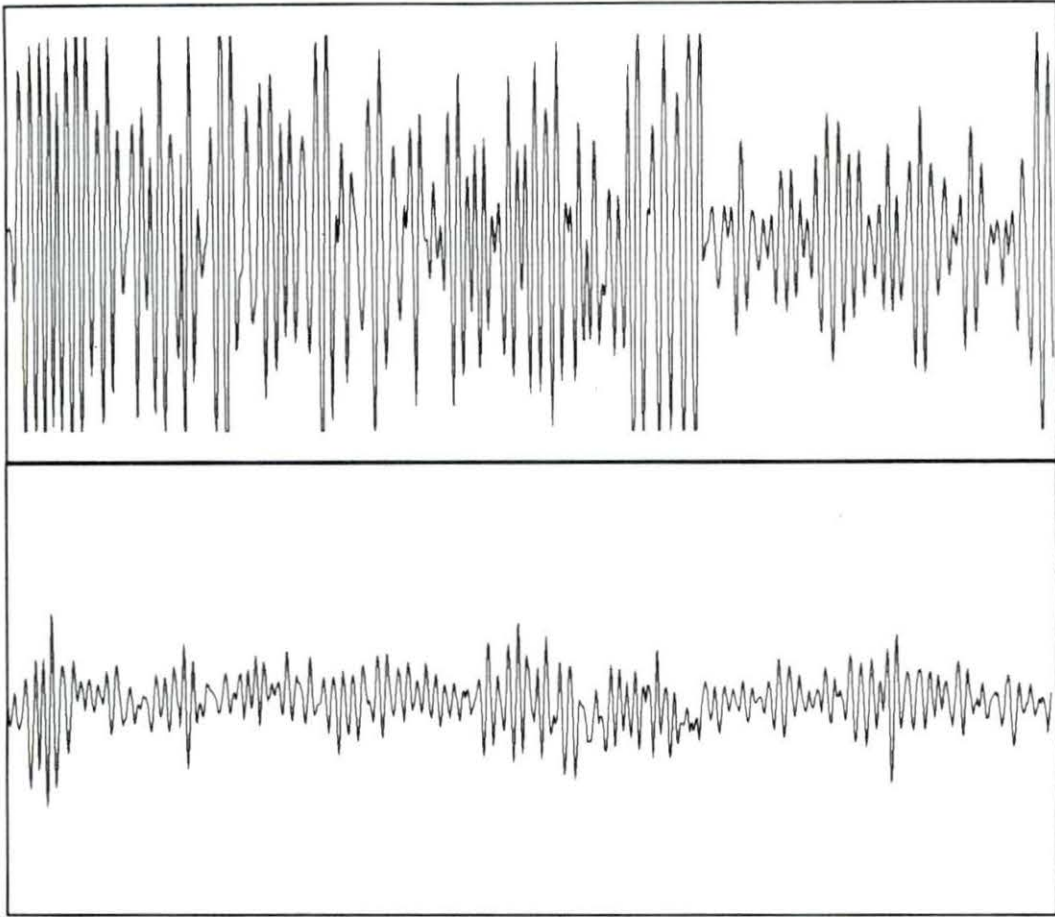


Figure 3.5 A-mode ultrasound reflections viewed from the dorsal side of the longissimus dorsi from 2 cm depth to 5.8 cm: a) sample with marbling score of moderately abundant 60%, b) sample with marbling score of slight 50%

order to calculate these values, the spectrum is smoothed using a 5 point moving average filter. Figure 3.6 shows a typical spectrum of a reflected signal and the results of the moving average filter. For grade representation, an integer between 0 and 100 was assigned with 0 representing "Practically Devoid 0%" and 100 representing "Very

Abundant 100%" (see figure 1.1). Table 3.1 shows the resulting center frequency and bandwidth values and the corresponding marbling scores for 21 carcass samples taken from the ventral side.

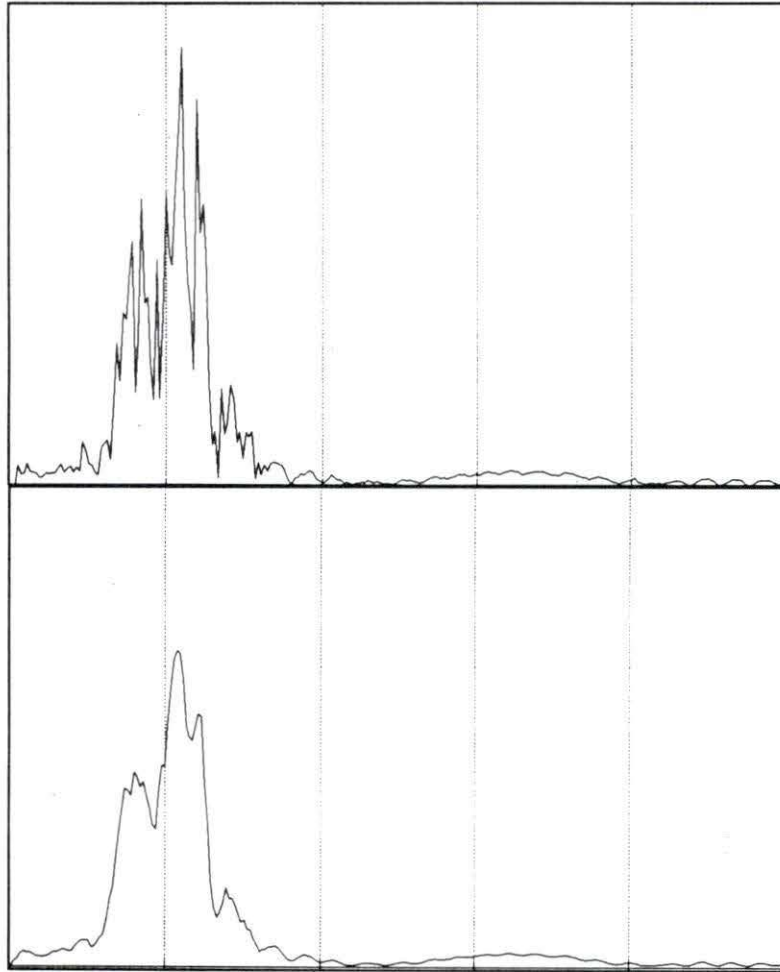


Figure 3.6 Spectrum of reflected signals (X-axis: 2 MHz/div, Y-axis relative amplitude): a) before filtering, b) after 5-point moving average filter

Table 3.1 Marbling score, spectral peak frequency, -12 dB bandlimits, and -12 dB bandwidth for 21 carcass samples

Marbling Score	Low Bandlimit Frequency	Peak Frequency	High Bandlimit Frequency	Bandwidth
23	1211	1875	2930	1719
24	1211	1719	2773	1562
24	1250	2227	2852	1602
25	1487	1719	2812	1325
25	1289	1758	2773	1484
28	1367	1641	2500	1133
28	859	2188	2773	1914
29	1367	2227	3008	1641
29	1289	1875	2734	1445
29	1289	1797	2695	1406
30	1523	1836	2422	899
31	1367	2188	2812	1445
31	1133	2383	2812	1679
31	1328	2188	2617	1289
32	1094	1875	2852	1758
32	1055	2148	2930	1875
32	1406	1875	2773	1367
34	1250	1953	2656	1406
35	1328	1523	2656	1328
36	1328	2148	2930	1602
40	1172	2109	2734	1562

Figures 3.7 and 3.8 show graphs of the -12 dB bandlimits and the peak frequency, respectively. These figures do not show a high correlation between the spectral information and the marbling score. One reason for this may be that all of the 21 carcass samples had marbling scores in the range of 23 to 40 (out of 0 to 100). A larger, more varied, data set may show a better correlation.

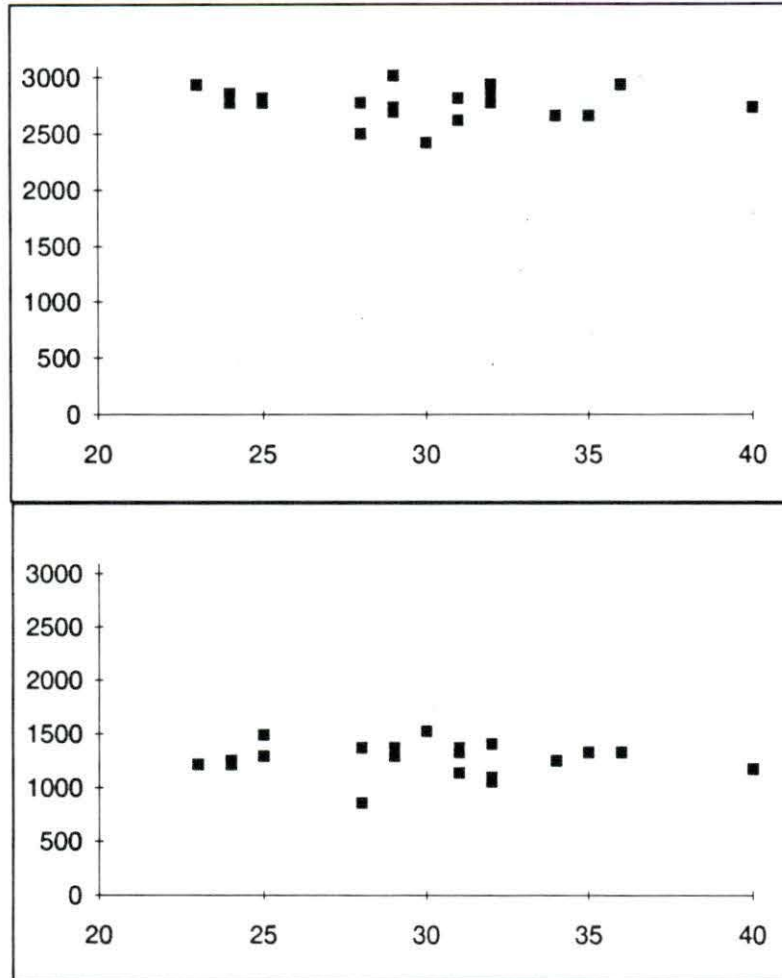


Figure 3.7 Marbling score versus -12dB bandlimits (Y-axis is frequency in kHz):
a) high frequency bandlimit, b) low frequency bandlimit

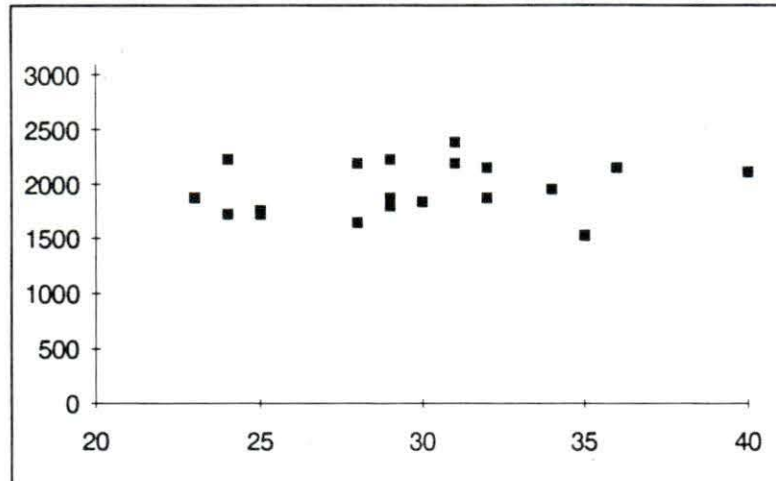


Figure 3.8 Marbling score versus peak frequency (Y-axis is frequency in kHz)

Recommendations

My recommendations would be to implement circuit improvements including:

- 1) Redesign the transducer array. The noise problem encountered with this system could be overcome with careful attention to transducer and multiplexer grounding.
- 2) Provide a regulated stimulus voltage for the transducer pulsing.
- 3) Improve the cutoff frequencies of the bandpass filter.
- 4) Develop a method to ensure consistent transducer coupling.
- 5) Attempt to optimize the circuit for lower power consumption.

With the proposed circuit improvements, a more complete statistical analysis of the carcass ultrasound signatures could be done. Once the exact signal processing needs

have been determined, the PC can be replaced by an imbedded microprocessor or digital signal processor, making a marketable, low cost, portable ultrasound beef grading system.

BIBLIOGRAPHY

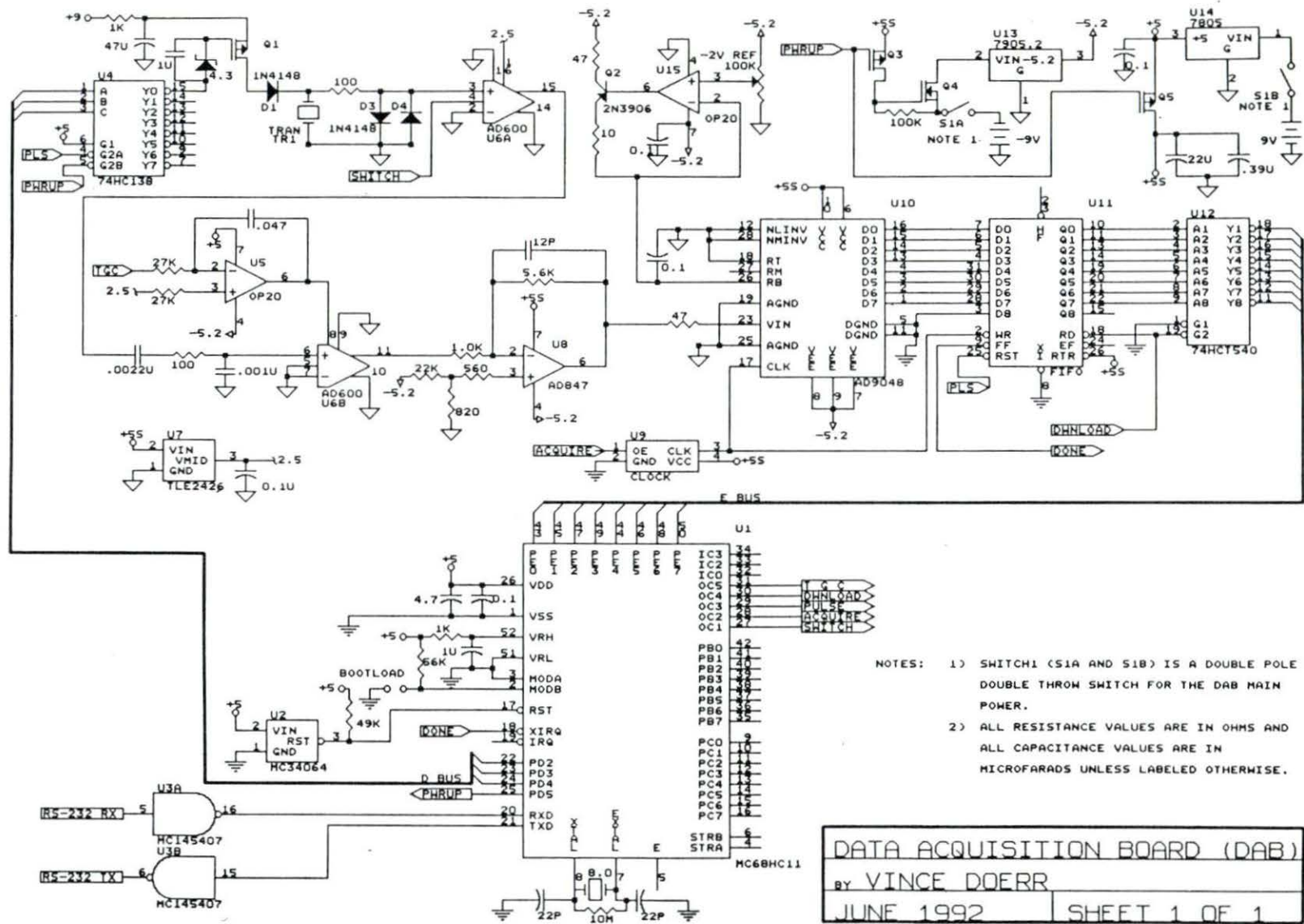
- Amin, Viren R. 1989. Ultrasonic attenuation estimation for tissue characterization. Masters Thesis. Iowa State University.
- Analog Devices. 1989. Data Conversion Products Databook. p3-515.
- Anselmo, V. J., J. Clark and P. M. Gammell. 1987. Electronic inspection of beef. JPL invention Report NPO-15477/4352. (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California).
- Brethour, John, R. 1990a. Increasing profitability in feedlot cattle with ultrasound technology. Kansas Agricultural Experimental Station Report of Progress #597.
- Brethour, John, R. 1990b. Relationship of ultrasound speckle to marbling score in cattle. Kansas Agricultural Experimental Station Report of Progress #597.
- Chang, Alan. 1991. Utility of the backscattered ultrasound A-mode signal for the quantitative grading of beef. Masters Thesis. Iowa State University.
- Feleppa, E. J. and M. Yaremko. 1987. Ultrasonic tissue characterization for diagnosis and monitoring. IEEE Engineering in Medicine and Biology, 18-26.
- Gore, J. C. and S. Leeman. 1977. Ultrasonic backscatter from human tissue: a realistic model. Physics in Medicine and Biology 22:317-326.
- Gatenby, J. C., J. C. Hoddinott, and S. Leeman. 1989. Phasing out speckle. Physics in Medicine and Biology 34:1683-1689.
- Gupta, V. N, P. K. Bhagat and C. E. Ott. 1982. Ultrasonic characterization of acute renal failure. Ultrasound in Medicine and Biology 8:249-261.
- Haumschild, D. J. and D. L. Carlson. 1983. An ultrasonic Bragg scattering technique for the quantitative characterization of marbling in beef. Ultrasonics (London) 21:226-233.

- Kuc, Roman, K. Haghkerdar and M. O'Donnell. 1986. Presence of cepstral peak in random reflected ultrasound signals. *Ultrasonic Imaging* 8:196-212.
- Parks, Bosoon and Dale Whittaker. 1990. Determination of beef marbling score using ultrasound A-scan. American Society of Agricultural Engineers. Paper number 90-6058.
- USDA. 1965. Official US standards for grades of carcass beef, USDA, C. N. M. S.
- Webster, John. 1978. Medical instrumentation application and design. Houghton Mifflin Company, Boston, 602pp.
- Wells P. N. T. 1969. Physical principles of ultrasonic diagnosis. Academic Press, New York, 12pp.
- Whittaker, A.D., B. Parks, and B. R. Thane. 1990. Principles of ultrasound and measurement of intramuscular fat. Department of Agricultural Engineering Report, Texas A & M University.
- Widyaatmadja, Lanny B. 1991. Attenuation measurement of the backscattered ultrasound A-mode signal for beef grading. Masters Thesis. Iowa State University.
- Woods, M. O., and C. A. Miles. 1986. Ultrasound speed and attenuation in homogenates of bovine skeletal muscle. *Ultrasonics (London)* 24:260-266.

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APPENDIX A. DATA ACQUISITION BOARD SCHEMATIC
DIAGRAM



- NOTES:
- 1) SWITCH1 (S1A AND S1B) IS A DOUBLE POLE DOUBLE THROW SWITCH FOR THE DAB MAIN POWER.
 - 2) ALL RESISTANCE VALUES ARE IN OHMS AND ALL CAPACITANCE VALUES ARE IN MICROFARADS UNLESS LABELED OTHERWISE.

DATA ACQUISITION BOARD (DAB)
 BY VINCE DOERR
 JUNE 1992 SHEET 1 OF 1

APPENDIX B. MICROCONTROLLER ASSEMBLY LANGUAGE
SOURCE CODE

*The following is the assembly language code for the Motorola 68HC11
*microcontroller.

*This code is used for digitizing an ultrasound signal and exporting this data serially.

*set assembler variables

DELAY	EQU	\$0000
TRAN	EQU	\$0002
GAIN	EQU	\$0003
PORTA	EQU	\$00
PORTD	EQU	\$08
PORTE	EQU	\$0A
DDRD	EQU	\$09
CFORC	EQU	\$0B
OC1M	EQU	\$0C
OC1D	EQU	\$0D
TCNT	EQU	\$0E
TOC1	EQU	\$16
TOC2	EQU	\$18
TOC3	EQU	\$1A
TOC5	EQU	\$1E
TCTL1	EQU	\$20
TFLG1	EQU	\$23
PACTL	EQU	\$26
BAUD	EQU	\$2B
SCCR2	EQU	\$2D
SCSR	EQU	\$2E
SCIINT	EQU	\$C4
XMIT	EQU	\$2F
RCV	EQU	\$2F
RCVSET	EQU	\$4000
WIDTH	EQU	\$20

*START OF THE MAIN PROG

*SETUP STACK AND INDEX

```
LDS  #$00FF
LDX  #$1000
CLRA
STAA DELAY
```

```

LDAA #1C
STAA TRAN

LDAA #30          SET BAUD TO 9600
STAA BAUD,X
LDAA #0C          ENABLE RS-232 COM
STAA SCCR2,X
LDAA #3C          SET UP PORT D FOR OUTPUT
STAA DDRD,X
LDAA #80
STAA OC1D,X      SEND TIMER 1 HIGH
STAA PACTL,X     SET UP TIMER 1 AS OUTPUT
STAA OC1M,X      SET PORTA PIN 7 AS TIMER 1 OUTPUT
LDAA #20
STAA PORTD,X     TURN POWER OFF
BRA WAIT

```

ON

```

LDAB #B2
STAB TCTL1,X
LDAB #E8
LDAA #1C
STAB CFORC,X    FORCE: OC2=LOW OC3=HIGH
STAA PORTD,X
LDAA #30
STAA PORTA,X
LDY #F000       DELAY TO ALLOW POWER TO STABLIZE

```

DUHLAY

```

DEY
BNE DUHLAY
RTS

```

DEPTH

*Get delay depth from computer via RS-232

```

BSR SERIAL
LDAB RCV,X      DOWNLOAD DELAY
CLRA

```



```
STD   DELAY
BRA   WAIT
```

*SUBROUTINE: SOFTWARE POLLING FOR RS-232 RCV DATA

SERIAL

```
LDAA  SCSR,X
TAB
ANDA  #$20
BEQ   SERIAL
RTS
```

*WAIT FOR A PULSE OR A DEPTH COMMAND FROM THE COMPUTER

WAIT

```
BSR   SERIAL
LDAA  RCV,X
REGURGITATE
LDAB  SCSR,X
ANDB  #$C0
BEQ   REGURGITATE
STAA  XMIT,X
CMPA  #$50
BEQ   GO
CMPA  #$44
BEQ   DEPTH
STAA  GAIN
BRA   WAIT
```

GO

```
BSR   ON      TURN POWER ON
```

PULSE

```
LDD   TCNT,X      GET CURRENT COUNT
ADDD  #$50        ADD A LITTLE TIME TO SET UP TIMERS
STD   TOC5,X      START INTEGRATION OF TIMER 5 (TGC)
ADDD  #$380       ADD MINIMUM WAIT FOR VALID TGC LEVEL
ADDB  GAIN        WAIT FOR GAIN COUNT (IE, SHIFT UP GAIN
CURVE)
ADCA  #$00
STD   TOC2,X      SET THE START OF DATA ACQUISITION
```

SUBD	DELAY	PULSE TRAN 'DELAY BEFORE DATA ACQ
PSHA		
PSHB		
SUBD	#WIDTH	
STD	TOC3,X	TURN ON CURRENT INTO THE TRANSDUCER
LDAA	#\$D3	
STAA	TCTL1,X	SET TIMER TO APPROPRIATE MODE
PULB		
LDAA	#\$20	
STAA	TFLG1,X	CLEAR ANY PENDING TIMEOUTS
CHECK		
LDAA	TFLG1,X	CHECK FOR TIMER 3 TIMEOUT
*		(IE. TRANSDUCER IS BEING PULSED)
ANDA	#\$20	
BEQ	CHECK	
PULA		
STD	TOC3,X	PULSE THE TRANSDUCER
ADDD	#\$15	
STD	TOC1,X	ENABLE INPUT TO THE AMP AFTER PULSE
CLRA		
STAA	OC1D,X	
LDAA	#\$F3	KEEP TIMERS 2,3,5 HIGH UNTIL DATA IS
DOWNLOADED		
STAA	TCTL1,X	
LDAB	DELAY	WHEN DELAY IS OVER, DATA IS BEING TAKEN
ASRB		
ASRB		
ASRB		
CLRA		
XGDY		
ABOVE		
DEY		DELAY TIME TO ALLOW DATA ACQUISITION TO
START		
BNE ABOVE		

*READ FIFO

```

LDY    #$0200      READ FIFO 512 TIMES
LDAB   #$30
CLRA
STAA   PORTA,X
STAB   PORTA,X
STAA   PORTA,X
STAB   PORTA,X
READING
LDAA   SCSR,X
ANDA   #$C0
BEQ    READING
CLRA
STAA   PORTA,X      SET READ\ LINE LOW
LDAA   PORTE,X      READ DATA
STAB   PORTA,X      SET READ\ LINE HIGH
STAA   XMIT,X       SEND DATA TO COMPUTER
DEY
BNE    READING

LDAA   #$80
STAA   OC1D,X       RE-INITIALIZE TIMER 1
LDAA   #$B2
STAA   TCTL1,X     RE-INITIALIZE TIMER 2 AND 3
LDAA   #$E8
STAA   CFORC,X

* LDAA   TRAN
* ADDA   #$04
* STAA   TRAN
* STAA   PORTD,X    SET UP MUX & DEMUX FOR NEXT TRANSDUCER
* CMPA   #$20
* BNE    PULSE      REPEAT UNTIL ALL 7 TRANSDUCERS ARE
PULSED
* CLRA
* STAA   TRAN
BSR    OFF
JMP    WAIT

```

OFF

CLRB

LDAA #\$20

STAA PORTD,X

STAB TCTL1,X

STAB PORTA,X

RTS

APPENDIX C. MICROSOFT QUICK BASIC SOURCE CODE

```

'Microcomputer source code
DECLARE FUNCTION ASCIITOINT% (CHARACTER AS STRING)
'used to aquire data 5-19-92 thru 6- on cattle. This
'   version has 5 consecutive depths, the user selects the
'   gain for the first depth
CONST yes = 1
CONST no = 0
CONST delay = 1000
DIM value(512, 10)
DIM software%(255)

'open the file that contains the assembled HC11 code.
OPEN "a:\HC11\bootload" FOR INPUT AS #2
count% = 0

'convert the ASCII hex nibbles to integer numbers
DO WHILE NOT EOF(2) AND count% < 256
    first$ = INPUT$(1, #2)
    second$ = INPUT$(1, #2)
    'convert the first and second (ASCII) hex digits to an
    integer(=number)
    number% = 16 * ASCIITOINT(first$) +
              ASCIITOINT(second$)
    software%(count%) = number%
    count% = count% + 1
LOOP

'pad the bootload code to 256 bytes (207='STOP' for HC11)
FOR i% = count% TO 255
    software%(i%) = 207
NEXT
CLOSE #2

'open serial port and wait for a break character from HC11
ON ERROR GOTO handler
OPEN "COM1:1200,N,8,1,cd0,cs0,ds0,RB512,BIN" FOR RANDOM AS 1
CLS

```

```

PRINT "Waiting for power to be applied to board (HC11 break character)"
breaking% = yes
break$ = INPUT$(1, #1)
breaking% = no
'send HC11 the character $FF to set BAUD to 1200
PRINT #1, CHR$(255);

```

```

CLS
PRINT "Break received"
junk$ = INPUT$(LOC(1), #1)

```

```

'bootload the HC11
FOR i% = 0 TO 255
    PRINT #1, CHR$(software%(i%));
NEXT

```

```

CLOSE #1

```

```

OPEN "COM1:9600,N,8,1,cd0,cs0,ds0,RB512,BIN" FOR RANDOM AS 1
CLS

```

```

path$ = "A:\DATA"
CHDIR path$
PRINT : PRINT

```

```

'determine what the highest extension A:\DATA\RAWDATA.xxx is

```

```

extention% = -1
alldone% = no
repeater:
    extention% = extention% + 1
    a$ = CHR$(((extention% \ 100) MOD 10) + 48)
    b$ = CHR$(((extention% \ 10) MOD 10) + 48)
    c$ = CHR$((extention% MOD 10) + 48)
    exten$ = a$ + b$ + c$
    FILES path$ + "\RAWDATA." + exten$
    IF alldone% = no THEN GOTO repeater
CLS

```

```
file$ = path$ + "\RAWDATA." + exten$
PRINT : PRINT "Data will be stored in: "; file$: PRINT
PRINT : PRINT "Each subsequent data file will add one to the extension": PRINT
```

```
FILES "*.*"
PRINT : PRINT
```

```
'determine the number of locations that the user wants
PRINT "Please enter the number of transducer locations for each animal";
INPUT ": ", locations%
IF ((locations% < 1) OR (locations% > 10)) THEN locations = 6
```

```
'trigholdoff:
'INPUT "please enter delay (in centimeters).....", dist!
'PRINT : PRINT
dist! = 1
IF dist! < .5 THEN dist! = .5
dlay% = dist! * 26.6667
IF dlay% > 255 THEN dlay% = 255
usec! = dlay% * .5
dist! = usec! * .075
```

```
gainset:
INPUT "Please enter gain as a percentage (0 - 100).....", gain%
IF gain% < 0 THEN gain% = 0
IF gain% > 100 THEN gain% = 100
gain% = gain% + gain% \ 2
IF ((gain% = 68) OR (gain% = 80)) THEN gain% = gain% + 1
PRINT #1, CHR$(gain%);
junk$ = INPUT$(1, #1)
```

```
CLS
```

```
again:
SCREEN 0
file$ = path$ + "\" + "RAWDATA." + exten$
PRINT "Next data set will be stored in: "; file$: PRINT : PRINT
```



```

PRINT "Type 'G' to change the gain"
PRINT "Type 'Q' to quit"
INPUT "Position transducer at location 1 and hit ENTER to acquire data.....", j$

CLS
j$ = LEFT$(j$, 1)
IF ((j$ = "g") OR (j$ = "G")) THEN GOTO gainset
IF ((j$ = "q") OR (j$ = "Q")) THEN END

OPEN file$ FOR OUTPUT AS #3 LEN = 4608
PRINT #3, "Number of locations = "; locations%

FOR position% = 1 TO locations%

    nextdelay% = dlay%
    nextgain% = gain%

    'for 5 different depths acquire signals from the transducer
    FOR num% = 1 TO 5
        PRINT #1, CHR$(&H44);
        FOR k = 0 TO 100: NEXT
        IF (nextdelay% > 255) THEN nextdelay% = 255
        PRINT #1, CHR$(nextdelay%);
        junk$ = INPUT$(1, #1)

        IF (nextgain% > 200) THEN nextgain% = 200
        IF ((nextgain% = 68) OR (nextgain% = 80)) THEN nextgain% = nextgain% + 1
        PRINT #1, CHR$(nextgain%);
        junk$ = INPUT$(1, #1)

        PRINT #1, CHR$(&H50);      'tell HC11 to pulse transducers
        junk$ = INPUT$(1, 1)

    DO
        count% = LOC(1)
        LOOP UNTIL count% = 512
        info$(num%) = INPUT$(512, #1)

```

```

nextdelay% = nextdelay% + (1.8 * 26.6667) \ 1
nextgain% = nextgain% + 50
NEXT

```

```

SCREEN 2

```

```

FOR index% = 0 TO 4
  PRINT #3, info$(index% + 1) 'store data for each depth
  FOR i% = 0 TO 511
    value(i%, index%) = ASC(MID$(info$(index% + 1), i% + 1, 1))
    'IF i% > 0 THEN LINE (i%, 50 + value(i% - 1, index%) / 2)-((i% + 1), 50
+ value(i%, index%) / 2)
  NEXT
NEXT
FOR index% = 0 TO 4
  FOR i% = 0 TO 505 STEP 5
    max = 0
    min = 255
    FOR k% = 0 TO 4
      IF (value(i% + k%, index%) > max) THEN max = value(i% + k%,
index%)
      IF (value(i% + k%, index%) < min) THEN min = value(i% + k%,
index%)
    NEXT
    x% = (i% \ 5) + (index% * 100)
    y1% = (35 * (index% + 2) - maxold / 5)
    y2% = (35 * (index% + 2) - max / 5)
    IF i% > 0 THEN LINE (x%, y1%)-(x% + 1, y2%)
    maxold = max
    z1% = (35 * (index% + 2) - minold / 5)
    z2% = (35 * (index% + 2) - min / 5)
    IF i% > 0 THEN LINE (x%, z1%)-(x% + 1, z2%)
    minold = min
  NEXT i%
NEXT index%

```

```

IF (position% < locations%) THEN PRINT "Position transducer at location";
position% + 1; " and ";
INPUT "hit ENTER ", junk$
CLS

```

```

NEXT position%

```

```

INPUT "Do you wish to save this data (Y or N)? ", save$
save$ = LEFT$(save$, 1)
IF ((save$ = "n") OR (save$ = "N")) THEN
  CLOSE #3
  GOTO again
END IF

```

```

PRINT #3, "gain count = "; gain%; " out of 200"
PRINT #3, "first delay = "; dlay%
PRINT #3, "data spacing = 1.8cm"

```

```

extention% = extention% + 1
a$ = CHR$(((extention% \ 100) MOD 10) + 48)
b$ = CHR$(((extention% \ 10) MOD 10) + 48)
c$ = CHR$((extention% MOD 10) + 48)
exten$ = a$ + b$ + c$

```

```

'CLS
PRINT : PRINT "Data has been stored in "; file$: PRINT
PRINT : PRINT "Please type identification information followed by ENTER."
PRINT : PRINT "Note: this information will appear in the file exactly as you type it."
INPUT "IDENTIFICATION > ", IDENT$
PRINT #3, IDENT$

```

```

CLOSE #3

```

```

GOTO again

```

```

handler:

```

```
SELECT CASE ERR
CASE 53
    'file not found
    alldone% = yes      'no more RAWDATA.xxx, so I'm done
    RESUME NEXT
CASE 57
    IF breaking% = yes THEN
        RESUME NEXT
    ELSE
        PRINT "Device I/O error"
        FOR kk% = 0 TO 10: PRINT CHR$(7); : NEXT
        RESUME
    END IF
CASE ELSE
    CLS
    'RESUME
    PRINT "I've fallen and I can't get up"
    FOR kk% = 0 TO 10: PRINT CHR$(7): NEXT
    PRINT "try me again soon....."
    ' PRINT : PRINT "type GO to run again"
    END
END SELECT
```

FUNCTION ASCIITOINT% (CHARACTER AS STRING)

temp% = ASC(CHARACTER\$)

IF ((temp% > 47) AND (temp% < 58)) THEN temp% = temp% - 48

IF ((temp% > 64) AND (temp% < 71)) THEN temp% = temp% - 55

ASCIITOINT% = temp%

END FUNCTION

APPENDIX D. DATA PROCESSING ALGORITHMS

```

'this program takes an input file, finds the 512 FFT, smooths this spectrum
' then calculates and stores the peak frequency, and -12 dB bandlimits
DECLARE SUB moveave (spectrum!(), smooth!(), n%)
DECLARE SUB BITRV (n%, XR!(), XI!())
DECLARE SUB R2FFT (n%, XR!(), XI!(), WR!(), WI!())
DECLARE SUB WTABLE (n%, WR!(), WI!())
DIM XR!(512), XI!(512), WR!(512), WI!(512), mag!(512), angle!(512), spec!(512)
DIM num%(512)
n% = 512
pi = 3.14159265#
k = 11

SCREEN 9
CLS
COLOR k
OPEN "d:\freq_tbl" FOR OUTPUT AS #2

top:
INPUT "Please enter the file you wish to process ", file$
OPEN file$ FOR INPUT AS #1

'for all five depths
FOR j% = 1 TO 5
  ave# = 0
  FOR i% = 1 TO n%
    INPUT #1, num%(i%)
    ave# = ave# + num%(i%) / n%
  NEXT i%
  IF j% = 2 THEN
    ' for the second depth remove TGC effects and DC bias
    count% = 0
    FOR i% = 1 TO n%
      count% = count% + 1
      XR!(i%) = (num%(i%) - ave#) / ((1.00224754#) ^ count%)
      IF (i% > 1) THEN LINE (i%, 100 - (126 - num%(i% - 1)) / 2)-(i% + 1,
100 - (126 - num%(i%)) / 2)
      XI!(i%) = 0
    NEXT i%
  
```

END IF

IF j% = 2 THEN

'for the second depth: find the FFT

CALL WTABLE(n%, WR!(), WI!())

CALL R2FFT(n%, XR!(), XI!(), WR!(), WI!())

CALL BITRV(n%, XR!(), XI!())

'convert REAL-IMAGINARY to polar

FOR i% = 1 TO 512

mag!(i%) = SQR(XR!(i%) * XR!(i%) + XI!(i%) * XI!(i%))

IF (XR!(i%) > 0) THEN angle!(i%) = ATN(XI!(i%) / XR!(i%))

IF ((XR!(i%) < 0) AND (XI!(i%) < 0)) THEN angle!(i%) = ATN(XI!(i%) /
XR!(i%)) - pi

IF ((XR!(i%) < 0) AND (XI!(i%) >= 0)) THEN angle!(i%) = ATN(XI!(i%) /
XR!(i%)) + pi

IF ((XR!(i%) = 0) AND (XI!(i%) > 0)) THEN angle!(i%) = pi / 2

IF ((XR!(i%) = 0) AND (XI!(i%) < 0)) THEN angle!(i%) = -pi / 2

NEXT i%

CALL moveave(mag!(), spec!(), 5)

'find peak frequency

max = 0

peak% = 0

FOR i% = 1 TO n% / 2

IF spec!(i%) > max THEN

max = spec!(i%)

peak% = i%

END IF

NEXT

'find -12 dB low cutoff

low% = 0

i% = 0

DO

IF spec!(i%) > max * .25 THEN low% = i%

i% = i% + 1

LOOP UNTIL ((i% > 256) OR (low% < > 0))


```

'find -12 dB high cutoff
high% = 0
i% = n% / 2
DO
  IF spec!(i%) > max * .25 THEN high% = i%
  i% = i% - 1
LOOP UNTIL ((i% = 0) OR (high% < > 0))

low% = low% * 39.0625
peak% = peak% * 39.0625
high% = high% * 39.0625
PRINT low%, peak%, high%

'display spectrum
FOR i% = 2 TO 256
  LINE (i% * 2, 320 - spec!(i% - 1) / 25)-(i% * 2 + 2, 320 - spec!(i%) / 25)
  LINE (i% * 2, 220 - mag!(i% - 1) / 25)-(i% * 2 + 2, 220 - mag!(i%) / 25)
NEXT
END IF
NEXT j%

FOR i% = 1 TO 5
  LINE INPUT #1, st$
  PRINT st$
NEXT

INPUT "enter grade number > ", gr%
PRINT #2, gr%, low%, peak%, high%

CLOSE #1
GOTO top
END

```

```
SUB BITRV (n%, XR!(), XI!())
'@@@@@@@@@@@@@ SUBROUTINE BIT REVERSAL FOR FFT
@@@@@@@@@@@@@
```

```
'SUB BITRV (N%, XR!(), XI!())
j% = 1
N1% = n% - 1
FOR i% = 1 TO N1%
  IF (i% >= j%) GOTO KEND2
  temp! = XR!(j%)
  XR!(j%) = XR!(i%)
  XR!(i%) = temp!
  temp! = XI!(j%)
  XI!(j%) = XI!(i%)
  XI!(i%) = temp!
KEND2:
  k% = n% / 2
KGEJ:
  IF (k% >= j%) GOTO JPLK
  j% = j% - k%
  k% = k% / 2
  GOTO KGEJ
JPLK:
  j% = j% + k%
NEXT i%
END SUB
```

```
SUB moveave (spectrum!(), smooth!(), n%)
```

```
place% = n% \ 2 + 1
```

```
FOR i% = 0 TO place%
  spectrum!(i%) = 0
  smooth!(i%) = 0
NEXT
```

```
FOR i% = place% TO 512 - place%
  smooth!(i%) = 0
```

```

FOR j% = i% - n% \ 2 TO i% + n% \ 2
    smooth!(i%) = smooth!(i%) + spectrum!(j%) / n%
NEXT
NEXT

END SUB

SUB R2FFT (n%, XR!(), XI!(), WR!(), WI!())
'@@@@@@@@@@@@@@@@@ RADIX-2 DECIMATION-IN-TIME FFT
@@@@@@@@@@@@@@@@@
'      []
,
'SUB R2FFT (N%, XR!(), XI!(), WR!(), WI!())

FOR P% = 1 TO 15
    M% = P%
    N2% = 2 ^ P%
    IF (n% = N2%) GOTO start
NEXT P%
PRINT , "N, IS NOT A POWER OF 2"
STOP

start:
    N2% = n%
FOR i% = 1 TO M%
    N1% = N2%
    N2% = N2% / 2
    I1% = 1
    I2% = n% / N1%
    FOR j% = 1 TO N2%
        C! = WR!(I1%)
        S! = WI!(I1%)
        I1% = I1% + I2%
        FOR k% = j% TO n% STEP N1%
            L% = k% + N2%
            TEMPR! = XR!(k%) - XR!(L%)
            XR!(k%) = XR!(k%) + XR!(L%)
            TEMPI! = XI!(k%) - XI!(L%)

```

```

XI!(k%) = XI!(k%) + XI!(L%)
XR!(L%) = C! * TEMPR! + S! * TEMPI!
XI!(L%) = C! * TEMPI! - S! * TEMPR!

```

```

NEXT k%

```

```

NEXT j%

```

```

NEXT i%

```

```

END SUB

```

```

SUB WTABLE (n%, WR!(), WI!())

```

```

'@@@@@ GENERATING SINE AND COSINE VALUES FOR FFT

```

```

@@@@@'

```

```

'SUB WTABLE (N%, WR!(), WI!())

```

```

WN! = 6.2831853# / (n% * 1!)

```

```

FOR k% = 1 TO n%

```

```

    PHI! = WN! * (k% - 1)

```

```

    WR!(k%) = COS(PHI!)

```

```

    WI!(k%) = SIN(PHI!)

```

```

NEXT k%

```

```

END SUB

```

APPENDIX E. DATA ACQUISITION BOARD BILL OF MATERIALS

Bill Of Materials June 15, 1992 8:44:37 Page 1

Item	Quant	Reference	Price	Discription
1	1	BT1	0.95	9V Battery
2	1	BT2	0.95	-9V Battery
3	4	C1,C10,C11,C12	0.40	0.1 uF Cap
4	1	C2,C15	0.10	4.7uF Cap
5	1	C3	0.10	1UuF Cap
6	3	C4,C5,C6	0.30	22pF Cap
7	3	C13,C14,C16	0.30	0.1uF Cap
8	1	C7	0.10	0.1uF Cap
9	1	C8	0.10	.01uF Cap
10	1	C9	0.10	.001uF Cap
11	1	C15	0.10	4.7uF Cap
12	1	C17	0.10	.047uF Cap
13	3	D1,D2,D3	0.05	1N4148 Diode
14	1	D4	0.15	4.3V ZENER
15	1	Q1	0.20	MOSFET N chan
16	1	Q2	0.15	2N3906 Transistor
17	3	Q3,Q4,Q5	1.20	MOSFET P chan
18	2	R1,R5	0.04	1 kohm Resistor
19	2	R2,R3	0.04	1.2 kohm Resistor
20	1	R4	0.02	10 Mohm Resistor
21	1	R10	0.02	1.2 kohm Resistor
22	1	R11	0.02	8.2 kohm Resisitor
23	2	R12,R14	0.04	47 ohm Resistor
24	1	R13	0.02	10 ohm Resistor
25	2	R15,R16	0.04	100 kohm Resistor
26	1	R6	0.02	820 ohm Resistor
27	1	R7	0.02	22 kohm Resistor
28	1	R8	0.02	27 kohm Reistor
29	1	R9	0.02	560 kohm Resistor
30	1	R17	0.02	100 ohm Resitor
31	1	TR1	30.00	TRANSDUCER
32	1	U1	20.00	MC68HC11 microcontroller
33	1	U2	1.20	MC34064 Reset

34	2	U3	4.50	MC145407 RS-232 driver
35	1	U4	0.40	74HC138 Decoder
36	2	U5,U15	2.00	OP20 OpAmp
37	1	U6	20.00	AD600 Amplifier
37.5	1	U7	0.69	TLE2426 Rail divider
38	1	U8	2.50	AD847 Amplifier
39	1	U9	2.50	20M CLOCK
40	1	U10	25.00	AD9048 ADC
41	1	U11	5.00	Dallas FIFO
42	1	U12	1.00	74HCT540
43	1	U13	0.60	7905.2 Regulator
44	1	U14	0.60	7805 Regulator
45	1	Y1	1.12	8.0M Xtal
46	1	PCB	32.00	PC Board