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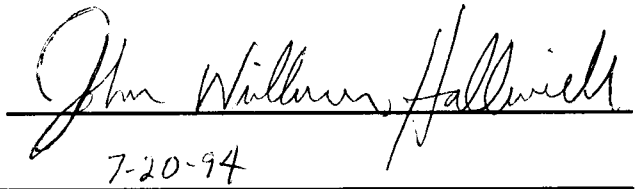
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# Design and Development of an Electronic Control System for an Electric Guitar

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

John William Halliwell

August, 1994

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## DEDICATION

This thesis is dedicated to my father and mother,

Col. George R. Halliwell, USAF Ret.

and

Mercedes A. Halliwell.

You taught me how to learn and gave me wings to fly.

## ACKNOWLEDGEMENTS

I would like to thank my major professor Dr. T. V. Blalock for his advice and encouragement. I would like also to thank the other members of my committee, Dr. E. J. Kennedy and Dr. H. P. Neff, for their assistance. Thanks to my colleagues at the Oak Ridge National Laboratory, for being a sounding board for my ideas (especially Andy Andrews, Charlie Nowlin, Mark Musrock and Alan Wintenberg) and to Mike Hileman for proofreading this manuscript.

Special thanks to Randy Kindsfather, who, not so many years ago, turned a co-op student into an engineer. A good mentor is not soon forgotten.

Most of all I want to thank my wife, Esther, for putting up with the many hours I spent working toward this degree and for being there to keep me going. Where was that list of home projects...

# ABSTRACT

The analog signal processing electronics for a microprocessor based electric guitar control system were developed. The design provides a broad tonal and gain control range with the unique feature of being fully digitally programmable. The circuit uses active analog gain and tone control circuits and analog transmission gates for control of pickup selection. A battery driven DC to DC converter is used to power the system.

In addition, a quantitative analysis of the electric guitar was carried out. String motion, magnetic pickups, passive filtering, and active filtering were evaluated. The circuit frequency response, transient response, and noise performance were considered.

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# LIST OF SYMBOLS

| | |
|---|---|
| ADC | Analog to digital converter |
| awg | American wire gauge |
| C | Capacitance (measured in Farads) |
| cm | Unit of length measure, centimeters (0.01 meters) |
| CMOS | Complementary Metal Oxide Semiconductor |
| DAC | Digital to analog converter |
| dB | Decibel |
| deg | Unit of angle, degrees |
| Dia | diameter |
| E | Energy, measured in Joules |
| e | electromotive force (emf) |
| ESR | Equivalent Series Resistance |
| f | frequency (hertz) |
| FFT | Fast Fourier Transform |
| H | Unit of Inductance, Henries |
| Hz | Unit of frequency, Hertz (1 cycle per second) |
| IC | Integrated Circuit |
| Kg | Unit of mass, kilograms (1000 grams) |
| kHz | Unit of frequency, kilohertz (1000 Hertz) |
| kohm | kiloohms (1000 ohms), a unit of electrical resistance |

| | |
|---|---|
| LED | Light emitting diode |
| $L_x$ | Inductance (measured in Henries) |
| m | Unit of length measure, meters |
| mA | Unit of current, milliamps (0.001 amps) |
| mJ | Unit of energy, millijoule (0.001 joules) |
| mV | Unit of voltage, millivolts (0.001 volts) |
| MathCad | Mathematical analysis program (Mathsoft, Incorporated) |
| Mohm | Unit of resistance, megaohm ($1 \times 10^6$ ohms) |
| Mux | Multiplexer |
| nF | Unit of capacitance, nanofarad ($1 \times 10^{-9}$ farads) |
| ohm | Unit of resistance, ohm |
| PSPICE | Circuit analysis program (Microsim, Incorporated) |
| Q | Circuit Q, energy stored per energy dissipated per cycle |
| R | Resistance (measured in ohms) |
| rad | Unit of radian frequency, radians (1 rad = $2\pi$ * frequency) |
| RC | Resistor/Capacitor network |
| rms | Root mean square |
| Rpm | Revolutions per minute |
| sec | Unit of time, seconds |
| SV | State Variable Filter |
| t | time (measured in seconds) |
| V | Unit of voltage, volts |

| | |
|---|---|
| v | Voltage (measured in volts) |

Greek Letters

| | |
|---|---|
| $\zeta$ | Damping coefficient |
| $\mu$ | Mass per unit length (Kg / cm) |
| $\pi$ | The mathmatical constant, Pi. |
| $\omega$ | Radian frequency (radians) |
| $\theta$ | Response phase angle (degrees) |

# 1. INTRODUCTION

## 1.1 Motivation

Playing a guitar requires skill and considerable practice. Beyond the basic skills required to play the guitar, a guitarist playing an electric instrument must adjust the instrument's controls for a desired sound. A typical electric guitar has two or three pickups, two volume controls, two tone controls, a pickup selection switch, and a pickup phase control switch. Given the myriad of possible configurations of pickup selection, tone and volume control settings, playing an electric guitar while trying to adjust all of these parameters can be overwhelming.

In general guitarists will vary the guitar volume while performing, but will usually stick to tried and true pickup and tone selections. This is often done not because these settings are optimum, but because it is too difficult to memorize and vary the guitar's controls for complex setups while playing.

While electric guitars have been around for nearly 70 years, only in the last 10 or 15 years has much work been done in the area of incorporating active electronics into guitar designs. With the advent of miniature components, especially surface mount components, more and more guitars are shipped from the factory with active electronics. In general the active electronics provide broader gain and tone control than can be achieved with passive components.

The work described in this thesis seeks to carry this trend even farther by combining the gain and tonal control flexibility of active electronics with digital

controllability. This will allow the use of a microprocessor to provide full programability of all the guitar's controls. The guitarist would be able to operate the instrument in a normal fashion, with the controls affecting the guitar's sound in real time, but at the touch of a button, store the desired setup for future recall.

## 1.2 Thesis Overview

The scope of this thesis is as follows:

In Section 2, the operation of the electric guitar and string vibration are discussed. The electric guitar is discussed in a general sense for the reader who is unfamiliar with electric guitar configurations. The analysis of string vibration will provide an insight into the effects of magnetic pickup location and operation on the guitar's tone.

In Section 3, the magnetic pickup and its response will be closely analyzed. This analysis builds on the work of Skilling (Skilling, 1962) and his analysis of the reluctance phonograph pickup. The magnetic and circuit response of the pickup will be analyzed. Here, the overall transfer function of the pickup, from string motion to voltage out, is discussed.

The information gained from the analyses of Sections 2 and 3 will be used in Section 4 to design the active Volume/Tone control circuit as well as to evaluate its performance. In addition, each of the other circuit blocks for the guitar control system will be analyzed and/or discussed in detail.

In Section 5, the framework for the system microcontroller firmware will be laid. This is an overview of a possible software configuration and does not cover actual microcode development.

In Section 6, the results of testing on an actual electric guitar with magnetic pickups will be detailed. Pickup response in both frequency and time domain is documented with lab test data. In addition, testing of each of the circuits designed in Section 4 will be reported.

Finally, in Section 7, conclusions as to the success of this effort will be made along with recommendations for possible future work.

In researching this topic, very little technical literature was found specifically related to magnetic pickups. Several databases were consulted, including the IEEE Onspec database, with only a handful of papers related to this topic located (none of which were in refereed journals). The best references found were texts on guitar (generally written in layman's terms with limited technical content) and the standard magnetic fields texts (which cover topics related to the magnetic pickup). It is hoped that this work will shed light on the operation of the electric guitar by combining the qualitative description of guitar operation generally found in the literature and a quantitative analysis of the guitar and its magnetic pickups.

# 2. THE ELECTRIC GUITAR

## 2.1 General

In order to better understand the operation of an electric guitar, one must first look at the basic structure and operation of the instrument (Denyer,1992; Brosnac, 1983; Erlewine, 1990; Hiscock, 1986). Figure 2.1.1 shows an outline of an electric guitar. The basic components of the guitar are identified in this figure.

A typical guitar has six strings. The strings are strummed or plucked to produce sound. The pitch of the musical note produced by the string is determined by a number of factors (see Section 2.3 for a detailed discussion of string motion) with three primary factors being string length, string tension, and string mass per unit length.

The neck is lined with metal rails referred to as frets. By pressing one's finger just behind a fret (on the nut side of the fret), the string's effective length and thus its vibrational pitch can be varied. Frets are spaced using the "Rule of 18" (Hiscock, 1986). Here, the total scale length is divided by 17.817 to yield the distance from the first fret to the nut. This procedure is repeated (divide remaining scale length by 17.817) to obtain the distance to each additional fret. The number of frets on the guitar neck varies by design from roughly 20 to 25 frets. Table 2.1.1 gives the fret spacing for a guitar with a 650 millimeter scale length (scale length is equal to the string length between the nut and bridge). Note that the fret spacing

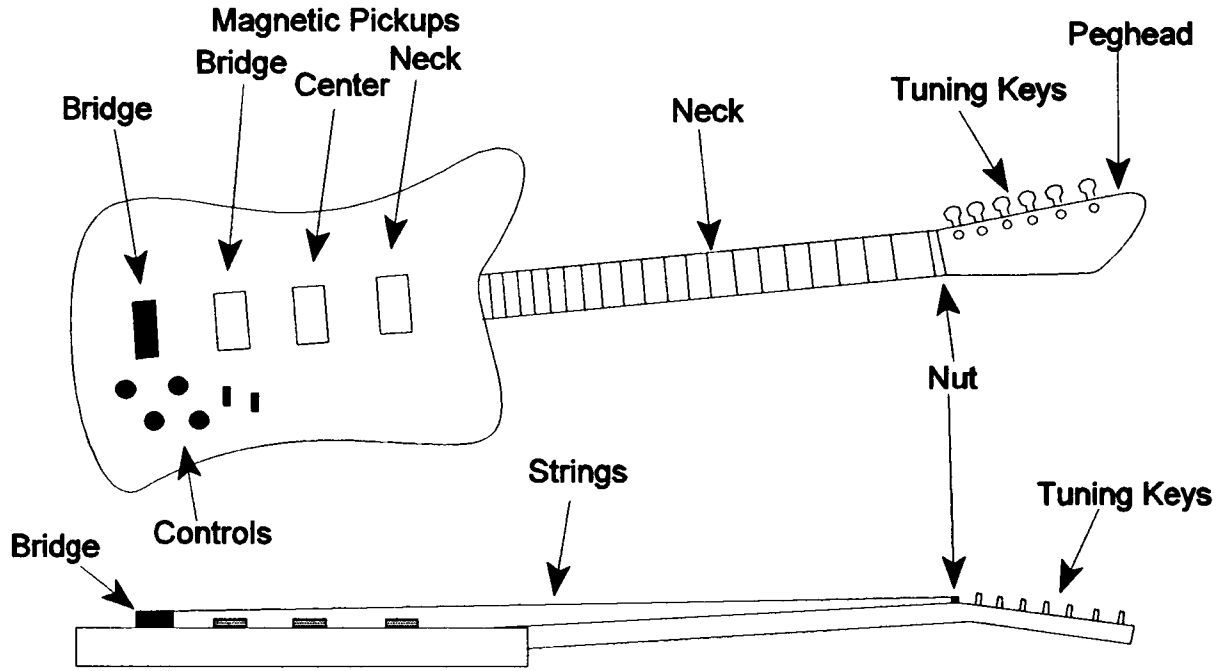



Figure 2.1.1 The Electric Guitar.

Table 2.1.1 Fret Spacing for a 650 mm Scale Guitar.

| Fret | Spacing (mm) | Distance From Bridge (mm) |
|---|---|---|
| 1 | 36.48 | 613.5 |
| 2 | 34.43 | 579.0 |
| 3 | 32.50 | 546.6 |
| 4 | 30.68 | 515.9 |
| 5 | 28.96 | 486.9 |
| 6 | 27.33 | 459.6 |
| 7 | 25.80 | 433.8 |
| 8 | 24.35 | 409.5 |
| 9 | 22.98 | 386.5 |
| 10 | 21.69 | 364.8 |
| 11 | 20.48 | 344.3 |
| 12 | 19.33 | 325.0 |
| 13 | 18.24 | 306.8 |
| 14 | 17.22 | 289.5 |
| 15 | 16.25 | 273.3 |
| 16 | 15.34 | 257.9 |
| 17 | 14.48 | 243.5 |
| 18 | 13.67 | 229.8 |
| 19 | 12.90 | 216.9 |
| 20 | 12.17 | 204.7 |
| 21 | 11.49 | 193.2 |
| 22 | 10.85 | 182.4 |

Source: Hiscock, Melvyn, 1986, Make Your Own Electric Guitar, Blandford Press, London, England.

decreases as you move from the nut to the bridge. The 12th fret is always located at the half scale length point. Fretting a string at the 12th fret produces a fundamental vibration frequency that is one octave above the unfretted, or "open", string.

In general the peghead is where the tuning keys are located. The tuning keys allow adjustment of string tension and are used to set the basic pitch of each string.

The strings on an electric guitar are made of a ferroelectric material (typically steel) to facilitate the use of magnetic pickups. The magnetic pickup develops a voltage output that is proportional to the string's velocity. Construction of magnetic pickups is covered in detail in Section 3. Output from the magnetic pickup is processed by a set of passive or active controls located just below the bridge. The simplest electric guitar design would use one magnetic pickup connected directly to an amplifier. Some typical controls found on the guitar are volume, tone, and pickup selection.

The bridge holds the strings in place on the guitar body. Design of the bridge determines the amount of coupling of string vibration to the body. Some bridge designs allow the bridge angle and thus string tension to be varied dynamically by use of a lever arm attached to the bridge plate. These are often referred to as "whammy bars" and are used to vary the pitch of all six strings on the guitar simultaneously. "Whammy bars" are commonly used in rock and roll style guitar playing. Presence of a whammy bar can affect the tonal qualities of a guitar

since it tends to absorb more energy from the string than a fixed bridge design. On most guitars the bridge also provides for adjusting the total length of each string. This is required to compensate for the additional tension added to a string when it is fretted near the center (12th fret) of the neck's total length. Adjusting the string's length to compensate for the tension change is referred to as setting the intonation of the guitar.

Acoustic guitars rely on careful design of the body to produce sufficient sound volume to be readily heard and to produce the desired tonal quality. Since electric guitars produce sound using magnetic pickups and electronic amplifiers, they are not required to produce sufficient acoustic volume to be heard. A typical electric guitar produces very little audible energy when its strings are lightly strummed. This distinction allows a great deal of freedom in the construction of an electric guitar and is a major reason for the distinct sound of the electric guitar.

In the electric guitar, the guitar body's major function is to provide a rigid attachment point for the strings. There is no requirement to enhance the coupling of string vibration to the air. This allows the body to be made of nearly any rigid material (note that the material, body shape and many other factors do influence the tonal quality of the guitar) and in any shape desired. In general, a heavy, rigid body will make the guitar have better sustain (sustain is a measure of the time a string vibrates after being plucked), while a lightweight, soft body will reduce the sustain. This is due to the fact that any motion of the string at the bridge tends to remove energy from the string and thus reduce, or "damp", its motion. The body and bridge

design can be used to enhance or suppress certain frequency components of string vibration and thus affect the guitar's tone.

Being freed from many of the design constraints of the acoustic guitar, electric guitars can be made with an emphasis on enhancing function, without sacrificing performance. A major determiner of the guitar's sound now becomes the magnetic pickups and electronics that process the guitar's signal. There are hundreds (if not thousands) of electric guitar designs that have been marketed over the years each with a unique tonal quality. The sections that follow will look at some of these designs and the physical constraints of guitar design in the area of magnetic pickup design, mounting and signal processing.

## 2.2 Electric Guitar Configurations

Magnetic pickups can be located at any point along a string's length to sense motion. The physical structure of the guitar, in general, limits pickup location to the area between the neck to body attachment and inside the bridge piece. This limits pickup location to roughly one quarter of the string's length near the bridge end of the string, as shown in Figure 2.2.1. In general, electric guitars are equipped with between 1 and 3 pickups. Figure 2.2.1 also shows typical pickup locations for one, two and three pickup installations. Pickup location affects the sound produced by the guitar by varying the amount of energy available from various string oscillation modes. Many guitarists refer to the bridge pickup as the "lead" pickup, since this position tends to contain more harmonic energy and thus produces a sharper, more

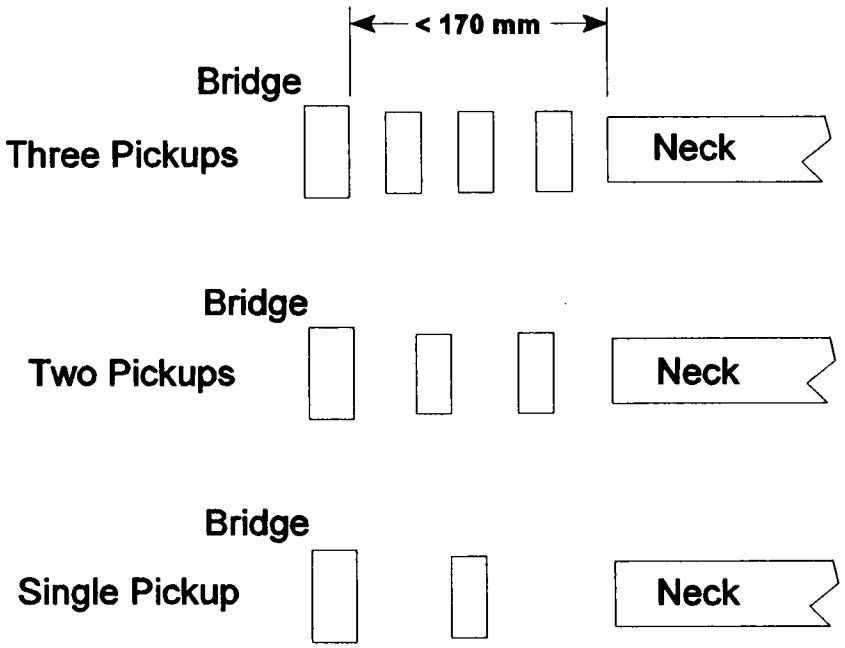



Figure 2.2.1 Typical Pickup Locations.

cutting tone. The neck pickup position is generally referred to as the "rhythm" pickup due to its mellower tone (more first and second harmonic energy). Note in Figure 2.2.1 that the three pickup configuration should provide the broadest tonal selection given the broader coverage of pickup locations. String motion and its influence on pickup location are discussed in detail in Section 2.3.

Most guitars on the market still rely on passive volume and tone control. Figure 2.2.2 shows the schematic of a single pickup installation. Resistor Rt in combination with capacitor Ct provide for tonal control (acting as a variable cut-off, single pole lowpass filter). Resistor Rv acts as a variable attenuator (or volume control). The circuit of Figure 2.2.2 is analyzed in detail in Section 3.3.

Note that the magnetic pickup could be directly connected to an amplifier without tone or volume controls. There are several drawbacks to direct connection including lack of tone and volume control at the guitar and the interaction of the amplifier input impedance with the pickup frequency response. The circuit of Figure 2.2.2 will also be affected by the amplifier input impedance but to a lesser extent. Active electronics can be used to make the effect of amplifier input impedance negligible. There are hundreds of alternate wiring schemes used to connect multiple pickups to an amplifier. The phase relationships, tone, volume and pickup selections are controlled by switches located on the face of the guitar.

Figure 2.2.3 shows a possible wiring scheme for a guitar with 3 pickups, where the phase of one of the pickups is user selectable. Rva allows the volume of pickup 2 to be varied independently of pickups 1 and 3. S2 provides five

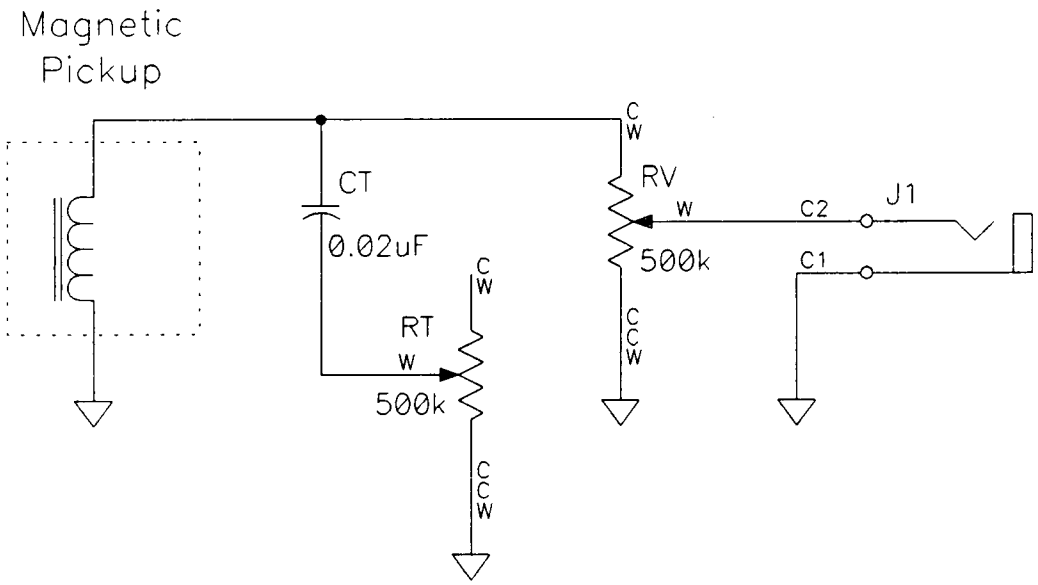



Figure 2.2.2 Single Pickup System Schematic.

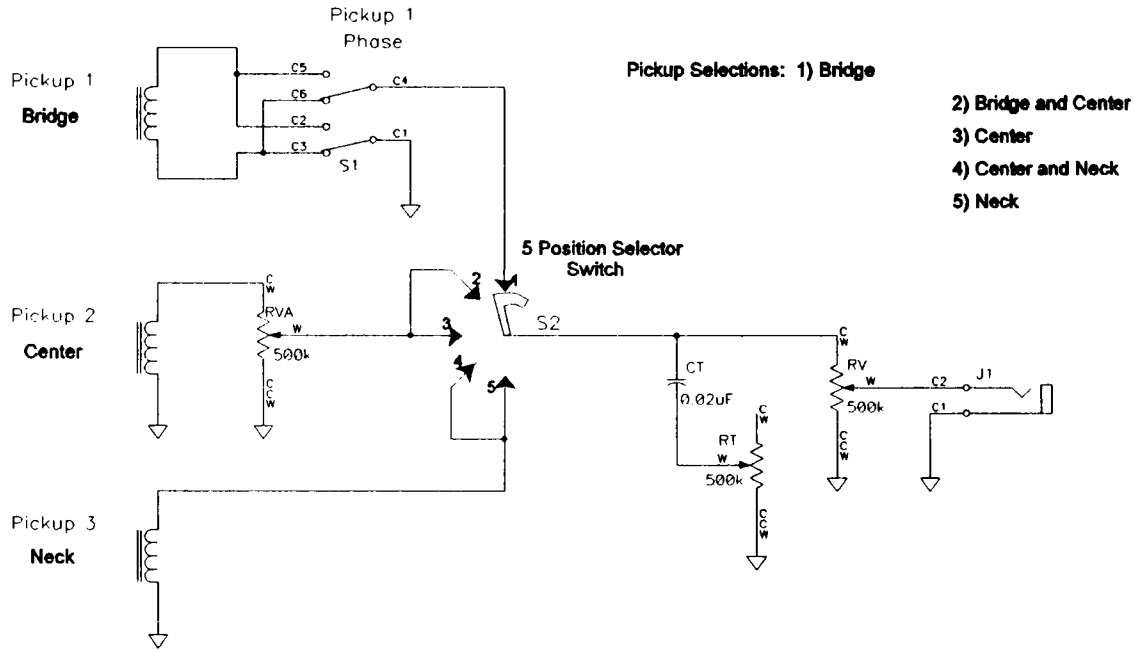



Figure 2.2.3 Three Pickup System Schematic.

possible pickup selections as listed in the figure. Rv acts as a master volume control for the guitar. One problem of having a master volume control is the widely varying signal levels produced for the various combinations of pickups. In general, the master volume would have to be set to a different position for each pickup selection to maintain a constant volume. S1 allows the output signal phase of pickup 1 to be inverted in relation to pickups 2 and 3. Operating one pickup out of phase from another pickup with a parallel connection tends to cancel signals that are common to both pickups. Some very unusual tonal qualities can be obtained using out of phase pickups.

Output from the guitar is connected by coaxial cable (terminated in 1/4" phono connectors) to signal processing equipment. Depending on the design of the guitar electronics, the cable capacitance can have a major effect on the guitar's tone.

## 2.3 The Physics of String Motion

Since electric guitars work by directly sensing string motion, understanding string motion is fundamental to predicting the performance of the instrument. In general, guitars are made with either six or twelve strings. Table 2.3.1 shows the fundamental tuning frequency for each string of a six string guitar. Note that this is "standard" tuning. Any number of alternate tunings have been used on guitars, but for simplicity, standard tuning will be assumed throughout this document.

Table 2.3.1 Guitar String Tuning.

| String Number | Typical Dia. (mils) | Musical Note | Frequency (Hz) | Tension at Pitch (N) |
|---|---|---|---|---|
| 1 | 9 | E | 329.6 | 59.59 |
| 2 | 11 | B | 246.9 | 49.96 |
| 3 | 16 | G | 196 | 66.61 |
| 4 | 24 | D | 148.6 | 71.76 |
| 5 | 32 | A | 110 | 69.89 |
| 6 | 42 | E | 82.4 | 67.56 |

Source: Denyer, Ralph, 1992, The Guitar Handbook, Alfred A. Knoph, Inc., New York.

When a guitar string is plucked, a pattern of standing waves develops along the string's length. This is due to the motion, induced by the pluck, propagating along the string and being reflected at the string's attachment points to the guitar's body. The basic equation for string motion (Tipler, 1976, Sears, 1989, and Hall, 1989) in this situation (string rigidly constrained on both ends) is

$$f = \frac{n}{2L}\sqrt{\frac{T}{\mu_m}} \quad , \quad n = 1, 2, 3, \ldots \quad , \qquad (2.3.1)$$

where f is the frequency of the string's vibration, T is the string tension, n is a positive integer, L is the string length, and $\mu_m$ is the string's mass per unit length. The value of n describes the string's mode of oscillation, where n = 1 denotes the fundamental, n = 2 denotes the second harmonic and so on. In SI units, typical values for the equation parameters are L = 0.65 m (meters), T = 60 N (newtons), and $\mu_m$ = 0.003 Kg/m (kilograms / meter). A plot of Equation 2.3.1 (f versus T) is shown in Figure 2.3.1. Note that doubling the string's oscillation frequency requires quadrupling the string's tension.

Equation 2.3.1 is derived assuming a perfectly uniform string. For actual strings the fundamental oscillation frequency and its harmonics as well as the node locations will vary since the string's mass per unit length is not uniform along the length of the string. Indeed, this may contribute to the unique "tone" of a guitar.

Figure 2.3.2 is a diagram of string vibration modes. Each mode represents a possible vibration pattern for a string that is rigidly supported at both ends. When

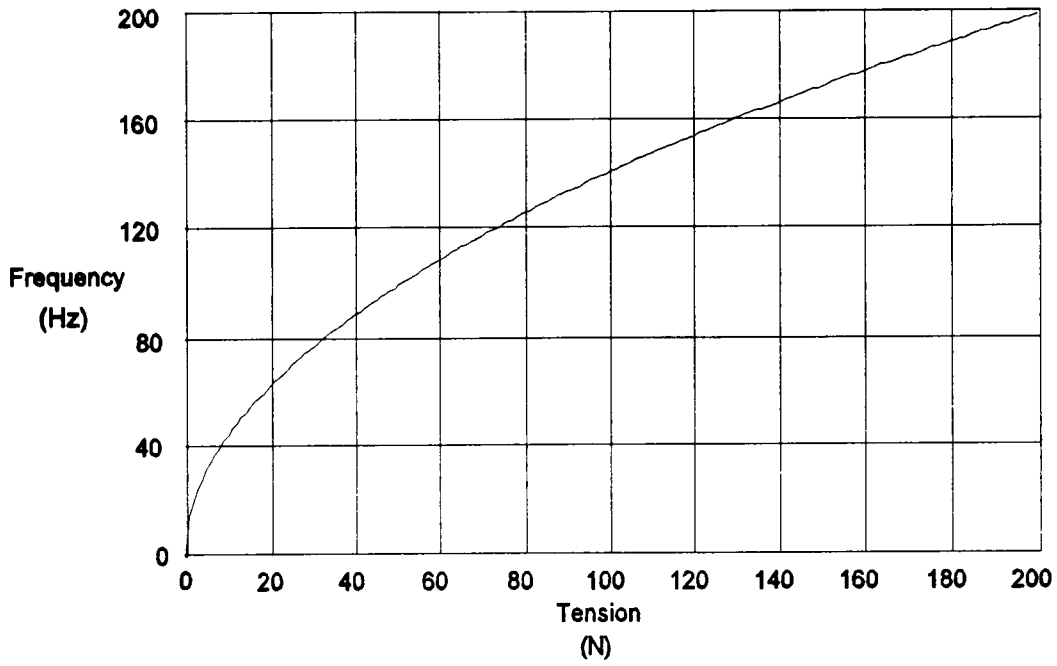



Figure 2.3.1 String Vibration Frequency versus String Tension for n=1, $\mu_m$=0.003 kg/m and L=0.65 m.

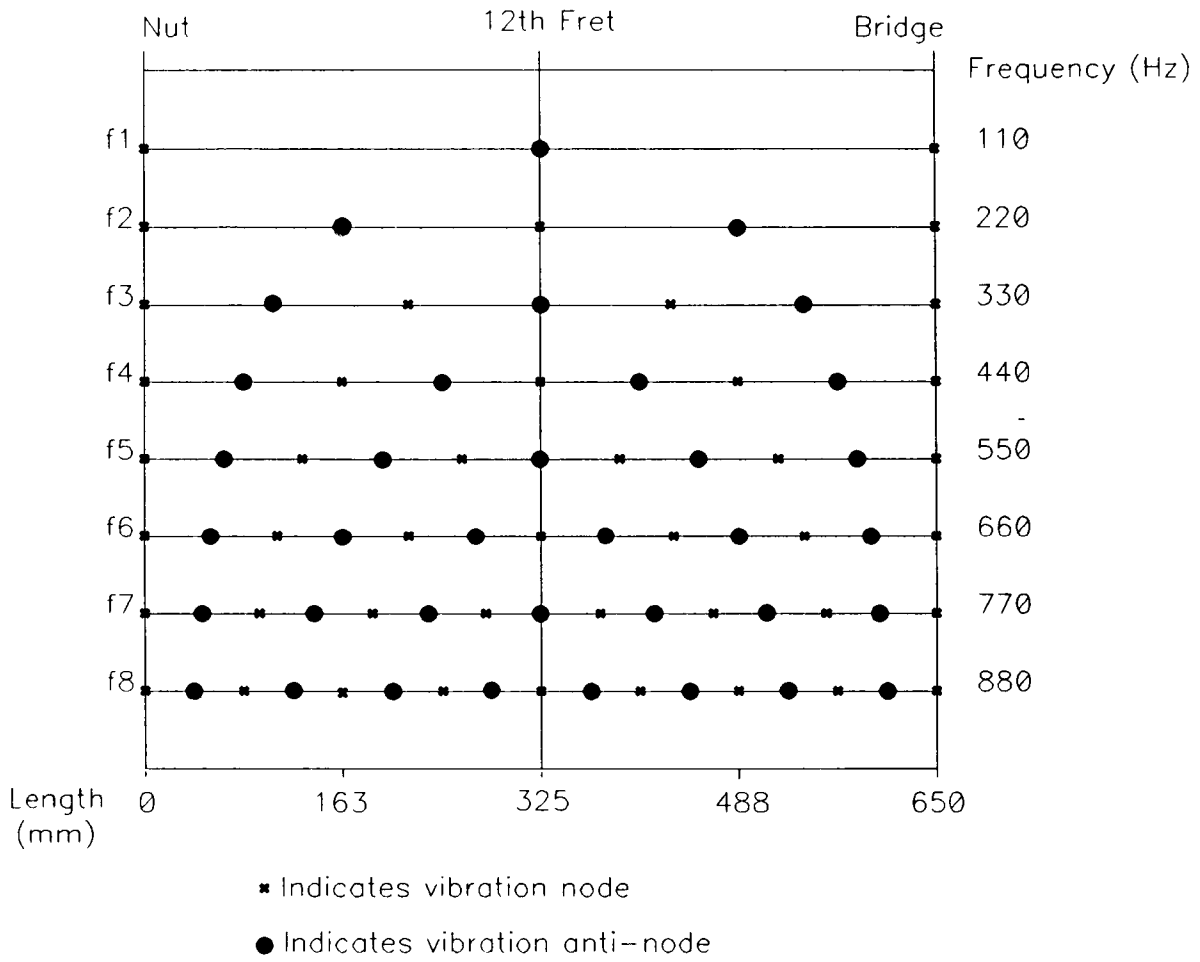



Figure 2.3.2 String Vibration Modes for n = 1 to n = 8 for the Open A String.

a string on the guitar is plucked, energy is transferred from the guitarist's finger or pick to the string. Which string oscillation modes are excited is a function of where the string is plucked along its length. The energy imparted to each mode is given by (Hall, 1989):

$$E_n = \left[\frac{k}{n^2}\right] \sin^2\left(n \pi \frac{X}{L}\right) \quad . \tag{2.3.2}$$

Here, k is a constant representing the energy input to the string, n is the mode number, L is the scale length, and X is the distance from the bridge to the point where the string was plucked . Figure 2.3.3 shows Equation 2.3.2 plotted for n = 1 to 4. Since this equation is symmetrical around the half scale length (12th fret), X can also represent the distance a string is plucked from the nut. Plucking the string near a node of one of the vibration modes will limit the amount of energy available to excite that mode. Plucking the string over the 12th fret (1/2 the scale length) will enhance the amount of fundamental vibration energy (n = 1) since this is the vibrational antinode (location of maximum string motion) for fundamental energy. Plucking the string over the 12th fret will limit the amount of second harmonic energy (n = 2) since this is a vibrational node (point where string motion is smallest) for the second harmonic. Guitarists use this fact to control, to some extent, the tonal quality of the notes being played.

It can be seen from Equation 2.3.2 that the higher order modes are more difficult to excite. High order modes also tend to decay more quickly (Hall, 1989)

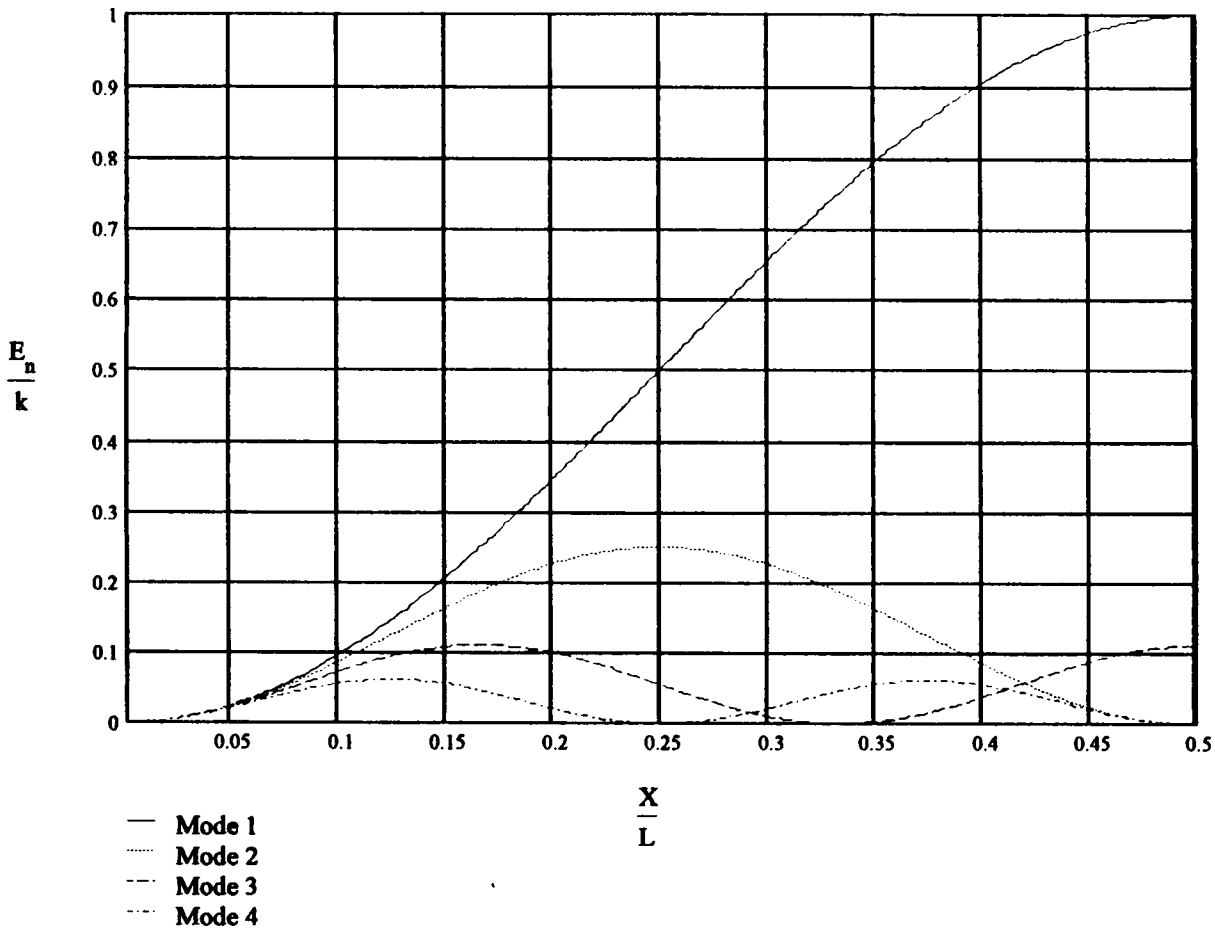



Figure 2.3.3 Normalized Energy Imparted to String Vibration Modes versus Pluck Position.

than low order modes due to increased string heating, more air resistance, and higher radiation efficiency at higher string vibration frequencies. Because of these non-uniform decay rates for the different modes, the tone of a guitar note changes dynamically after a string is plucked (lower order modes becoming dominant as time passes).

Figures 2.3.2 and 2.3.3 also provide a notion of how pickup location can be of great importance. Locating a pickup at a vibrational node for a particular mode will limit the amount of energy available from that mode. In general more high order harmonics are present for a pickup located near the guitar bridge, while a softer (more fundamental) tone is found by locating the pickup near the guitar neck. Since fretting a string changes its effective length the node structure would be different for each fret used. This makes it very difficult to clearly predict the specific frequency content for a given pickup position other than the general comments made above.

An equation for the string position versus time relative to the magnetic pickup pole requires some simplifying assumptions. Here the string is assumed to be constrained to vibrating in one plane (parallel with the top of the pickup) and that only the fundamental (n =1) mode of vibration has been excited. This is illustrated in Figure 2.3.4. Given these assumptions string position versus time can be computed as

$$p(t) = A\cos(2\pi f_v t)\, e^{\left(-\frac{t}{\tau}\right)} \quad . \tag{2.3.3}$$

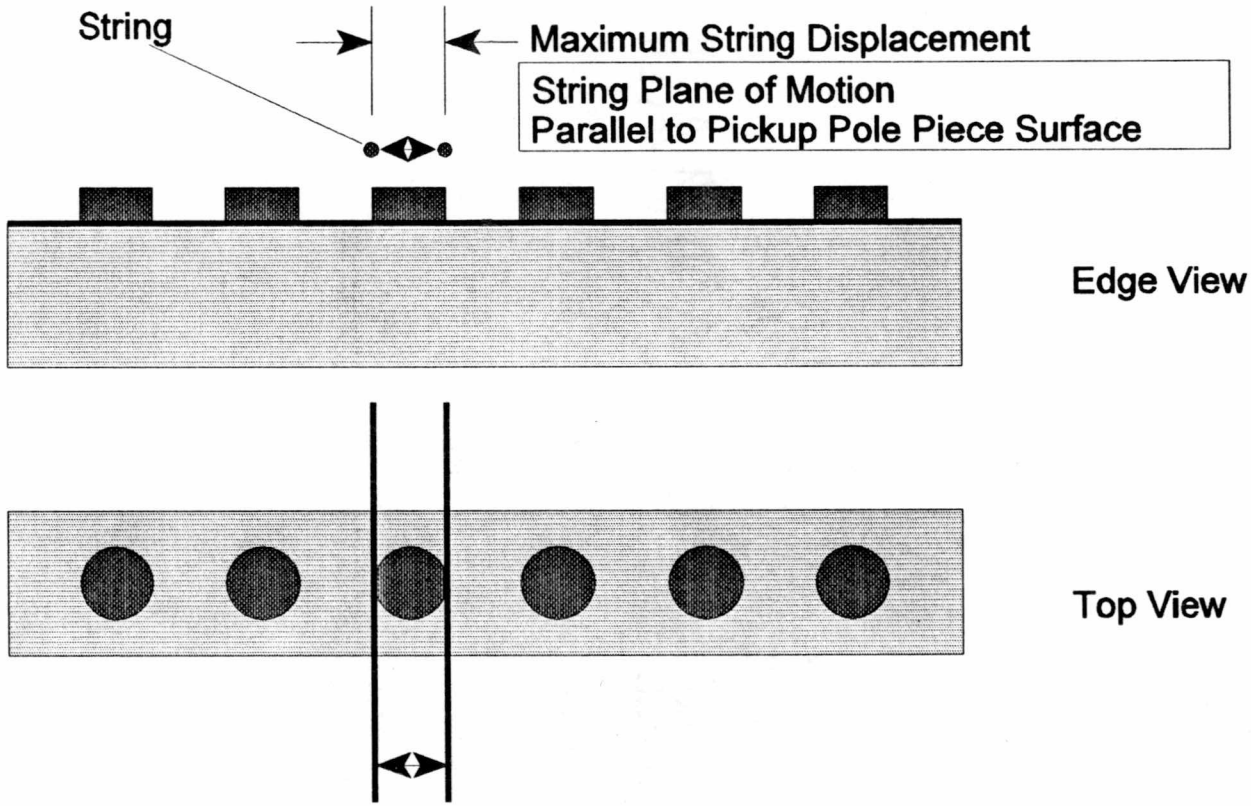
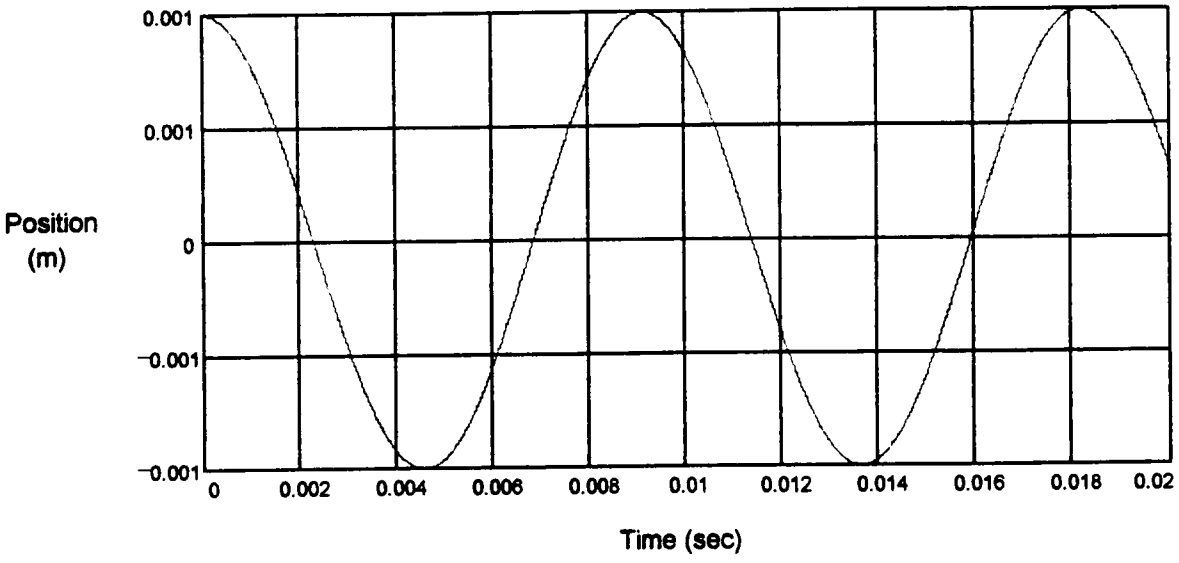



Figure 2.3.4 String Motion in One Plane.

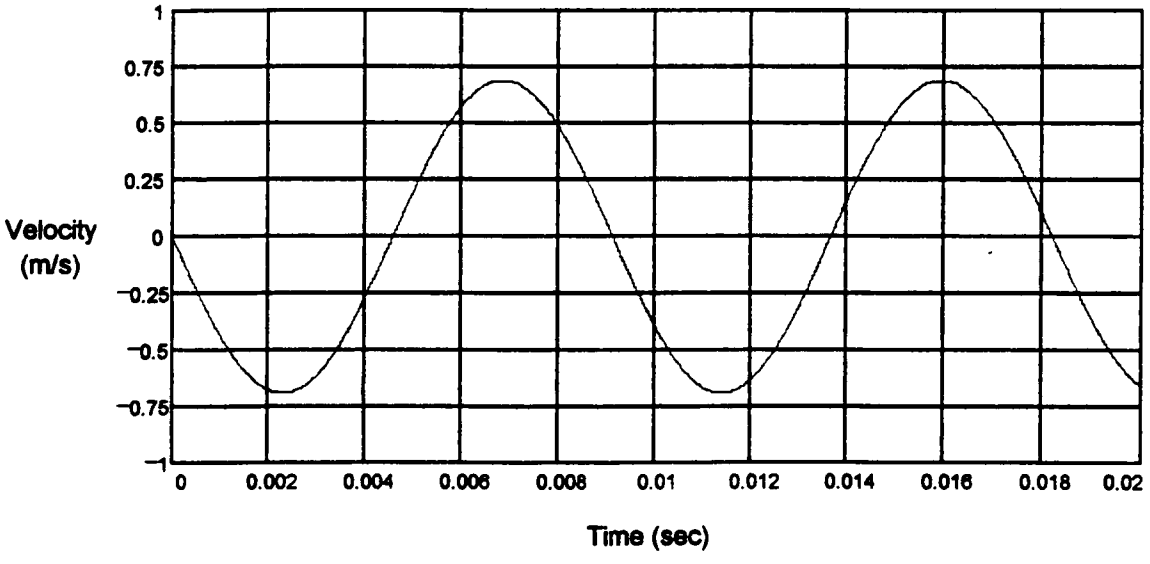
Here, A is the string displacement and $f_v$ is the vibration frequency. The cosine function is used since the string starts at maximum displacement before being released. The exponential term accounts for the decay of the string's motion. For a string where there are no mechanical losses (vibrating in vacuum, perfectly rigid ends, no string heating, etc...) the time constant $\tau$ would be infinite. For a real string, at $t = \tau$ the string vibration amplitude A, will be reduced 36.8% of its original value. A typical value of $\tau$ is 2 seconds. Equation 2.3.3 can be used to compute the string velocity. For simplicity $\tau$ is assumed to be infinite (no decay of string motion). Here

$$v(t) = -2\pi f_v A \sin(2\pi f_v t) \quad . \tag{2.3.4}$$

The sign of v(t) in Equation 2.3.4 is dependent on the selection of the origin for the position. Equations 2.3.3 and 2.3.4 are plotted in Figure 2.3.5. Note that the string velocity is zero at the peaks of string motion and is maximum as the string passes over the magnetic pickup pole piece. Note also that the maximum velocity value is proportional to the initial string displacement and the vibration frequency. Applying Equation 2.3.4 to the open A string vibrating at 110 Hz for an initial displacement of 1 mm, the peak velocity would be 0.69 m/s. For a real string neither the plane of motion nor vibration modes are constrained.




(a)




(b)

Figure 2.3.5 String Position in Meters (a) and String Velocity in Meters/sec (b) versus Time.

# 3. THE MAGNETIC PICKUP

## 3.1 Background

The basic sensing element of the electric guitar is the magnetic pickup. The pickup converts a small (typically less than 2 mm peak to peak motion) string vibration into a voltage that can be processed and amplified as required by the guitarist. Figure 3.1.1 shows an outline of the structure of a typical pickup (Brosnac, 1983 and Lemme, 1981). Pickups are made using permanent magnet pole pieces, and a very fine wire coil (typically #43 awg wire). The coil can have from 5000 to 10000 turns. Most pickups produce tens of millivolts of output when a string is plucked. The components of the pickup are often potted using epoxy resin or bee's wax. This is done to prevent microphonics (movement of the magnetic components from vibration of the strings or guitar body which produce an output voltage, much the same as a microphone). At high volume levels, microphonics can cause high pitched feedback from the guitar pickup to occur.

The permanent magnet pole pieces are used as a magnetic bias. Flux from each permanent magnet is directed toward it's associated string. A ferromagnetic plate is often used at the base of the pickup to better contain the stray magnetic field. Some of the flux lines from the permanent magnet pole piece return to the base of the magnet through the string as shown in Figure 3.1.2. Any motion of the string alters the flux path length and thus produces a changing magnetic field at the coil which produces an output voltage.

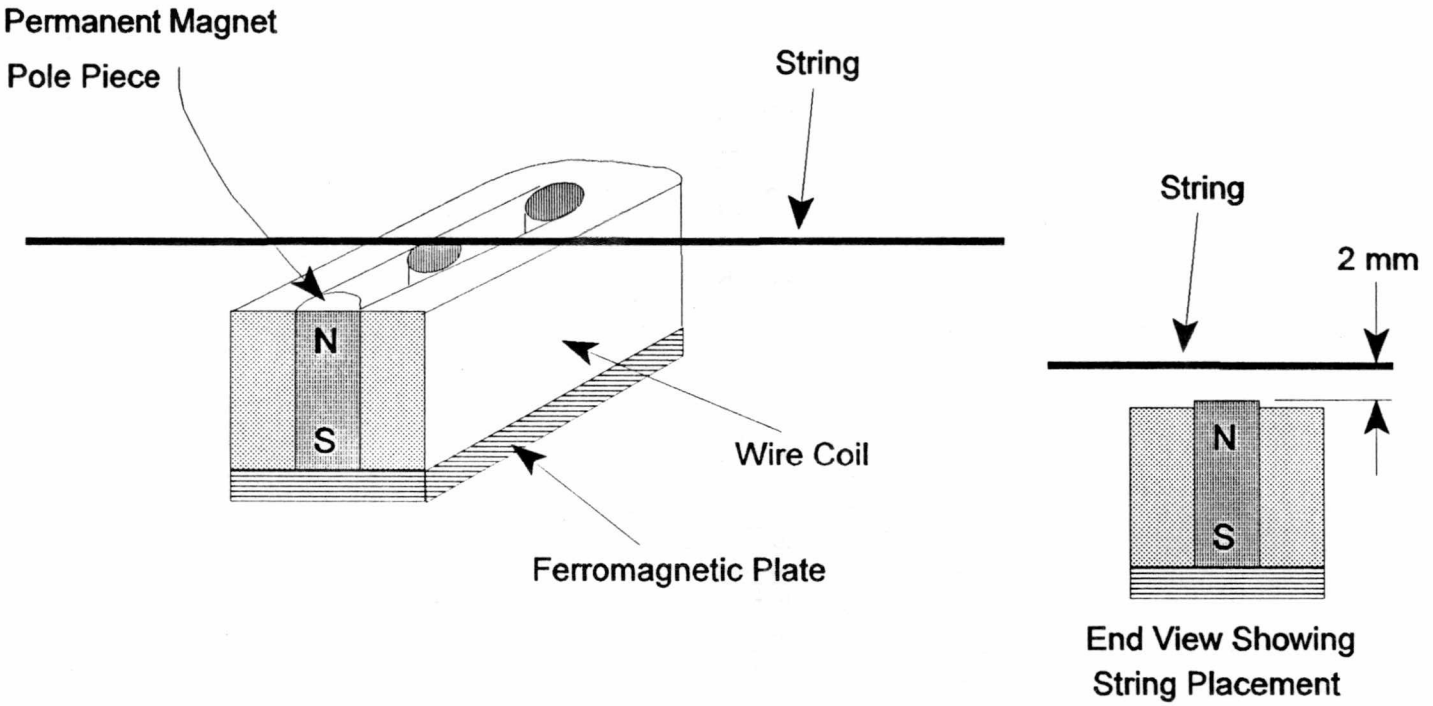
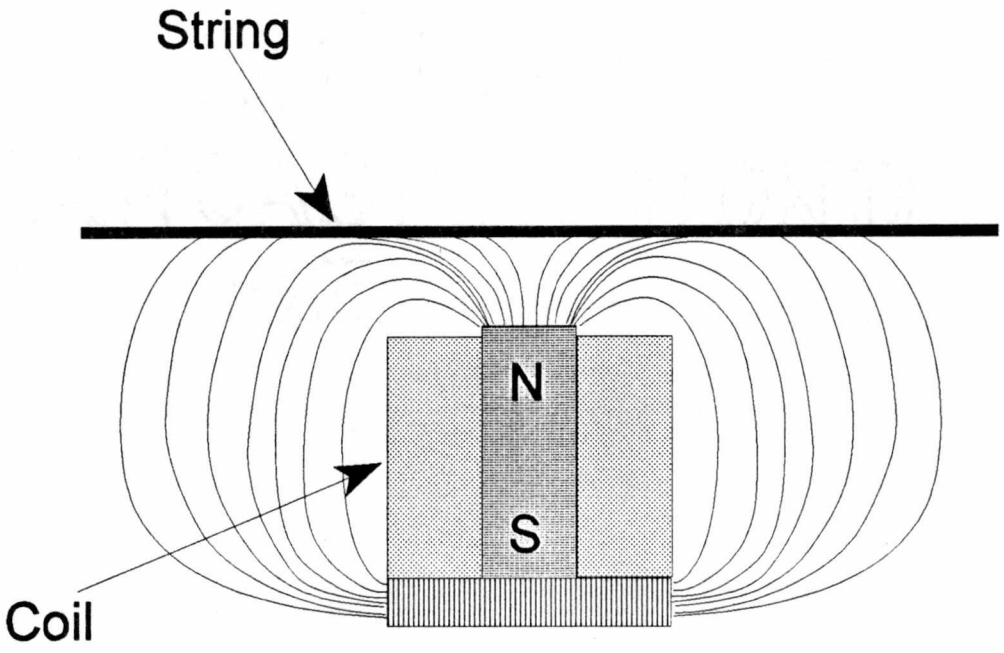



Figure 3.1.1 Magnetic Pickup Cutaway View.




End View
Crossection

Figure 3.1.2 Magnetic Pickup Flux Path.

Since the strings on a guitar have a roughly 5 to 1 range of diameters, some amplitude variation occurs from string to string. Some guitar pickups employ varying permanent magnet pole piece heights or provide adjustable pole piece heights to allow this affect to be compensated for. By moving the pole piece closer to the string, more flux couples to the string and thus the output voltage is increased for a given string motion.

Magnetic pickups are very susceptible to interference from stray magnetic fields. Pickup of unwanted AC field (typically at 60 Hz and it's harmonics) hum is a common problem in the presence of transformers and fluorescent lighting. A number of pickup configurations have been developed to combat stray field pickup. These alternate pickup designs are discussed in Section 3.4.

### 3.2 The Pickup Response

In order to calculate the magnetic pickup response to string motion one must consider three major items. Namely, string motion, the pickup magnetic response, and the pickup circuit response. In Section 2.3 string motion was discussed in detail. In this section the pickup magnetic response will be analyzed and the result combined with those of Section 2.3 to yield the total pickup magnetic response. Finally, this result will be used in Section 3.3 to compute the pickup's total response (string motion to voltage out of the pickup electrical circuit).

The ability to empirically analyze three dimensional magnetic circuits by hand is, in general, limited to those situations where the magnetic flux path is both

well defined and constrained. Magnetic systems with a well defined flux path can often be reduced to a one dimensional magnetic circuit (Del Toro, 1968). In the case of the guitar pickup, developing an analytic description of the magnetic pickup would be nearly impossible. The complex magnetic field geometry of the pickup results from the fact that a majority of the flux lines from the permanent magnet follow paths that do not involve the string or magnetic structure of the pickup. These alternate paths are difficult to predict and involve the materials that surround both the bottom and top areas of the pickup which are typically non-ferromagnetic. Thus, much of the flux is contained in large, poorly defined, fringing fields.

With these limitations in mind, it is worth considering a magnetic circuit problem that is closely related to the guitar pickup but can be reduced to a simple magnetic circuit equivalent. Such a magnetic transducer is the reluctance phonograph pickup, which has been analyzed by Skilling (Skilling, 1962). Figure 3.2.1 shows the basic structure of the reluctance pickup. A moving ferromagnetic pivot alters the flux path for a permanent magnet and coil assembly. If the moving pivot's motion is limited to a small fraction (u) of the total gap length (w) then the coil output voltage can be computed as

$$e = \mu_o \frac{N \mathcal{F} A V_{el}}{w^2} \quad , \tag{3.2.1}$$

where N is the number of turns in the coil, $\mathcal{F}$ is the magnetic driving force of the permanent magnet, A is the cross-sectional area of the gap, $\mu_o$ is the permitivity of

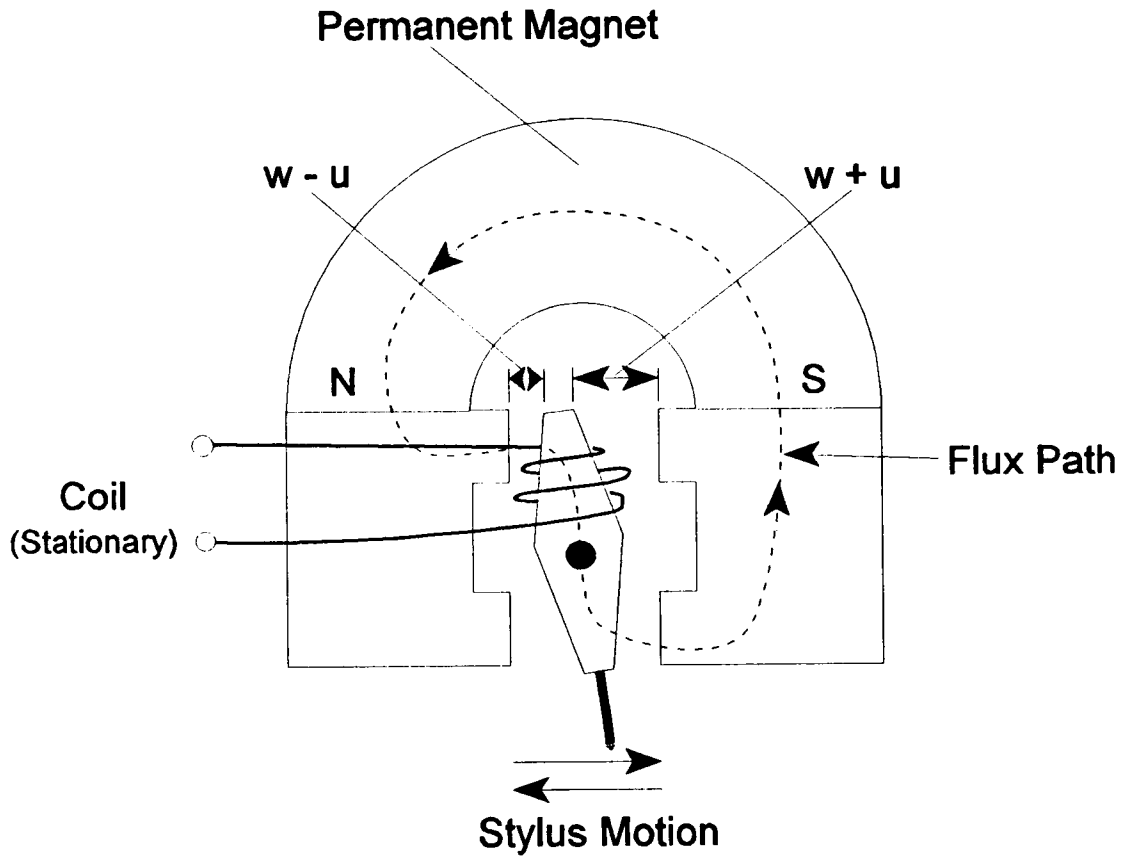



Figure 3.2.1 The Reluctance Phonograph Pickup.
Adapted from: Skilling, Hugh Hildreth, 1962, Electromechanics, John Wiley & Sons, Inc., New York.

free space, w is the gap length, and $V_{el}$ is the moving pivot velocity. Note that $\mathcal{F}$, A and w are fixed by the geometry of the pickup. This can be generalized to the guitar pickup by noting that the guitar string acts much the same as the moving pivot, altering the flux path for the coil/magnet assembly. Here the cross-sectional area A, the gap size, and the magnetic driving force are not well known. These parameters will be combined (A, $\mathcal{F}$, and w) into the constant k1. Then, Equation 3.2.1 can be written as

$$e(t) = k1\ N\ V_{el}(t) \quad . \tag{3.2.2}$$

Using the string velocity computed in Section 2.3, but ignoring the sign of the velocity (Equation 2.3.4, repeated here for the reader's convenience)

$$v(t) = 2\pi f_v A \sin(2\pi f_v t) = V_{el} \quad , \tag{2.3.4}$$

we have the total pickup response as

$$e(t) = k1\ N\ 2\pi f_v A \sin(2\pi f_v t) \quad . \tag{3.2.3}$$

Note that the polarity of e(t) would be determined by the magnetic circuit (ie., the location of the north and south magnetic poles of the permanent magnet). Here, e(t) is proportional to both the amplitude of the string motion and the frequency of

the string vibration. As f increases it is anticipated that the value of A decreases limiting the amount of peaking that will occur at higher frequencies. Experimental testing which verified the relationships of Equation 3.2.3 is presented in Section 6.1.

### 3.3 Circuit Characteristics

Now that the relationship of string motion to pickup output voltage has been described, one must look at the equivalent circuit of the magnetic pickup. Figure 3.3.1 shows the equivalent circuit of a magnetic pickup. Lp accounts for the inductance of the pickup coil and is generally in the range of several henries. Cp is the stray interwinding capacitance of the pickup and is generally in the range of 100 to 300 picofarads. Rp represents the ohmic resistance of the coil wire and is generally in the 5000 to 15000 ohm range. Vs represents the pickup output voltage described in Equation 3.2.3. It can be seen that the pickup will have at least a second order transfer function with a series resonant peak due to the inductance and capacitance found in the pickup. The resonance will occur at

$$f_{res} = \frac{1}{2\pi\sqrt{L_p C_p}} \quad . \tag{3.3.1}$$

The Q of the resonance is determined by Rp, where a large value of Rp reduces the Q. The resonance in usually in the 5000 to 15000 Hz range. Note that external

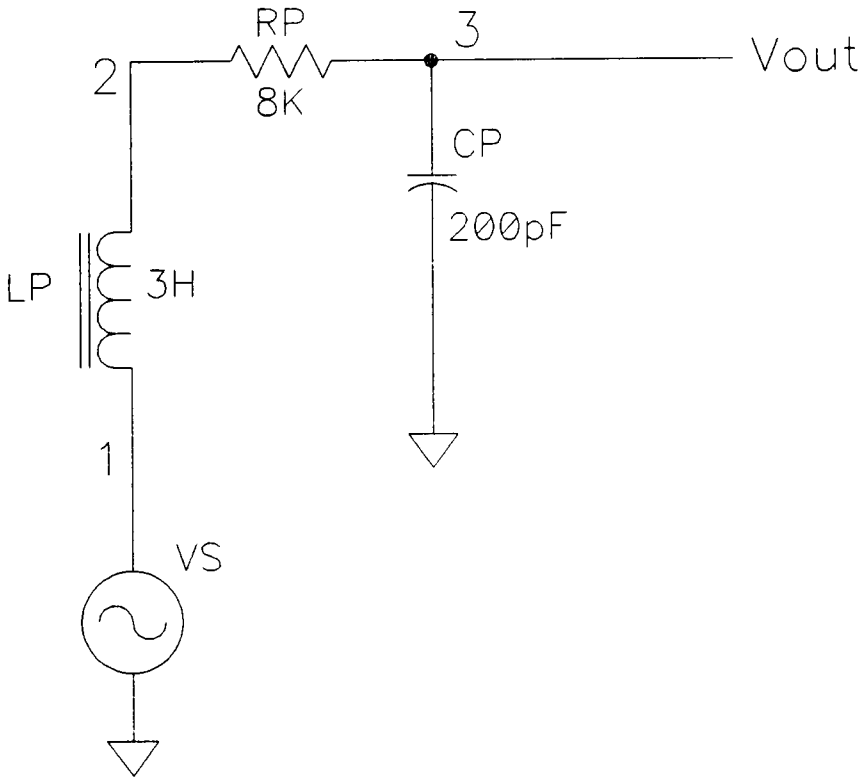



Figure 3.3.1 The Magnetic Pickup Equivalent Circuit.

loads will affect both the circuit Q (resistive loading) and the resonance (inductive and capacitive loading).

The tonal qualities of the pickup can be changed by varying Lp, Rp and Cp. Note that these three parameters are not independent. For example, increasing Lp by adding more turns to the coil will also increase Rp if the same size wire is used and may increase Cp. Lp will also be affected by the materials used in the pickup structure (bobbin and magnetic materials). Cp is mainly influenced by the tightness of the coil wire and how the coil wire was layered on the bobbin (a coil wound with uniform, controlled wire placement will exhibit a different capacitance than a coil that has it's wire layered at random). These complex interrelationships make tonal adjustment much more of a "trial and error" procedure.

The pickup equivalent circuit of Figure 3.3.1 can be readily analyzed by hand to yield the complex frequency response (s-domain) as

$$g(s) = \frac{(2\pi f_o)^2}{s^2 + 2\zeta(2\pi f_o)s + (2\pi f_o)^2} \quad . \tag{3.3.2}$$

For Equation 3.3.2

$$\zeta = \frac{Rp}{2}\sqrt{\frac{Cp}{Lp}} \tag{3.3.3}$$

and

$$f_o = \frac{1}{2\pi\sqrt{Lp\,Cp}} \quad . \tag{3.3.4}$$

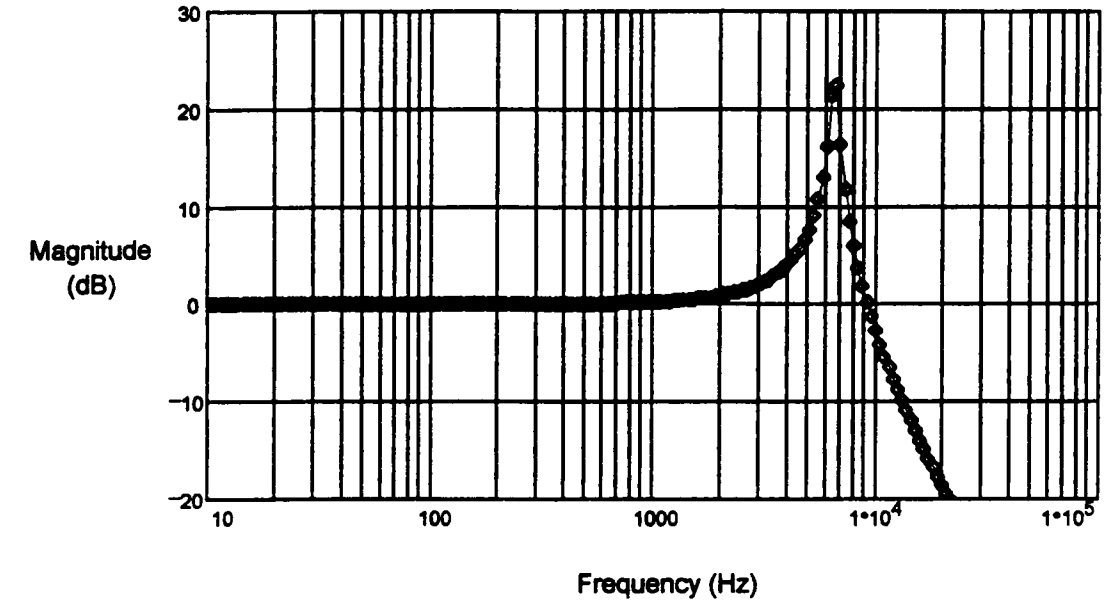
Note that the value of $f_o$, for typical values of Lp and Cp, is within the audio frequency range and may have a profound influence on the high frequency response of the pickup. The magnitude and phase response of Equation 3.3.2, after substituting s = j2πf, is shown in Figure 3.3.2 (plotted using MathCad 3.1) for the circuit values of Figure 3.3.1. Figure 3.3.3 shows the results of a PSPICE analysis of the circuit for magnitude (again, using the circuit values shown in Figure-3.3.1). Figure 3.3.4 shows the results of a PSPICE analysis of the transient step response of the circuit for a 1 volt step input. Note that the pickup circuit rings for several milliseconds after the step due to the high un-loaded circuit Q. The PSPICE circuit listings can be found in Appendix A.

In order to see the complete response of the magnetic pickup, Equations 3.2.3 and 3.3.2 must be combined into a composite response equation for the pickup (with $f_v = \frac{-js}{2\pi}$)

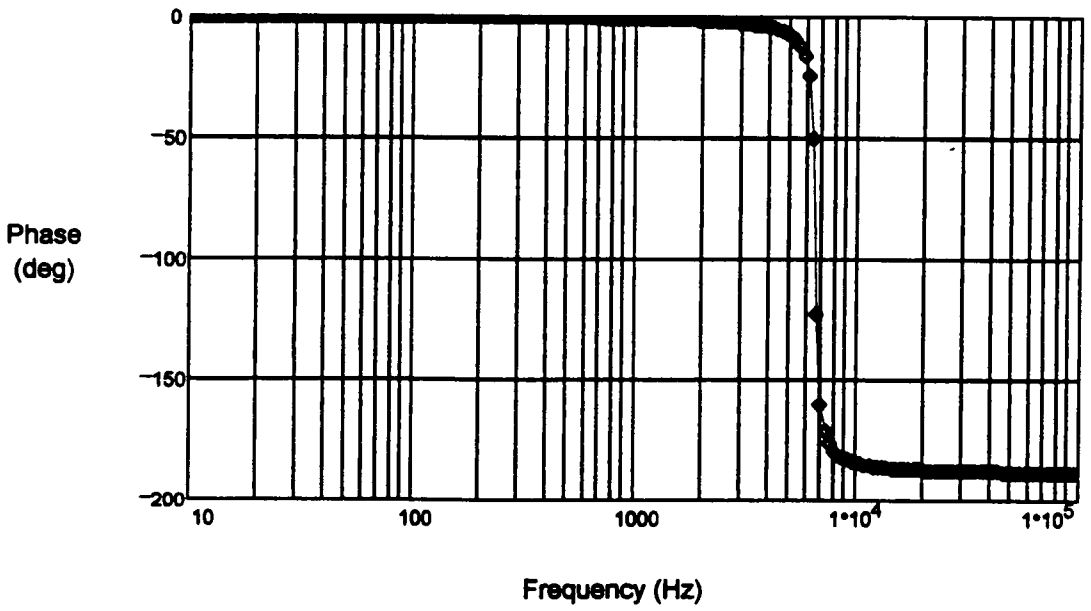
$$g_c(s) = \frac{(2\pi f_o)^2}{s^2 + 2\zeta(2\pi f_o)s + (2\pi f_o)^2}\, k1\, N(-js)A \quad . \tag{3.3.3}$$

Since the functional relation of A versus s is not known, equation 3.3.3 is not plotted.

In Figure 3.3.5 the pickup equivalent circuit has been combined with a typical guitar tone control scheme.




(a)




(b)

Figure 3.3.2 The Magnetic Pickup Response Magnitude (a) and Phase (b) with No Load (for circuit of Figure 3.3.1).

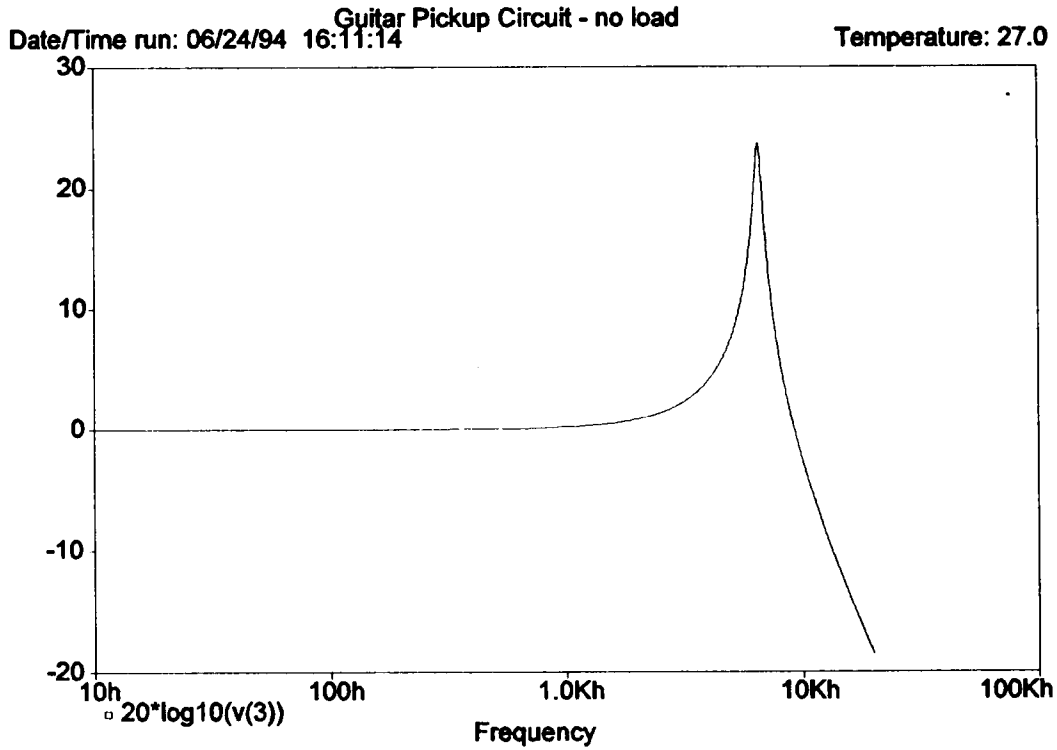



Figure 3.3.3 The Magnetic Pickup Frequency Response with No Load, Predicted Using PSPICE (for the Circuit of Figure 3.3.1).

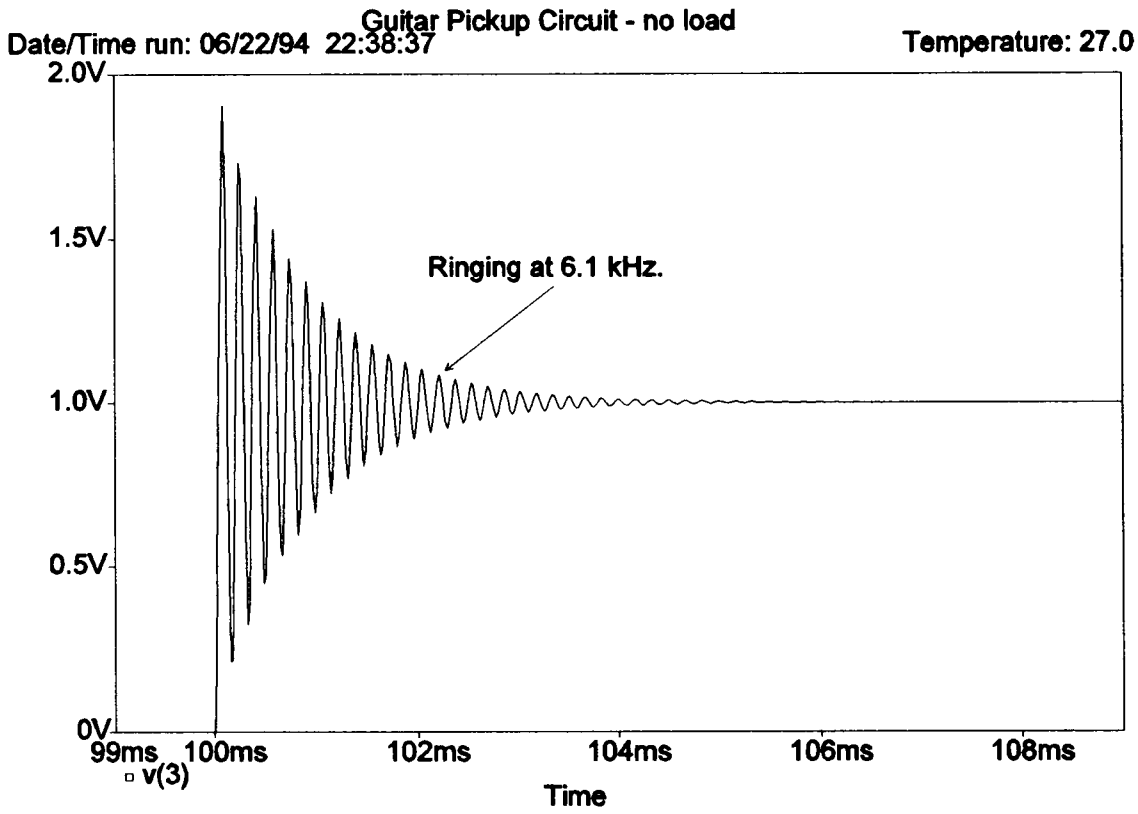



Figure 3.3.4 The Magnetic Pickup Transient Response with No Load, Predicted Using PSPICE (for the Circuit of Figure 3.3.1).

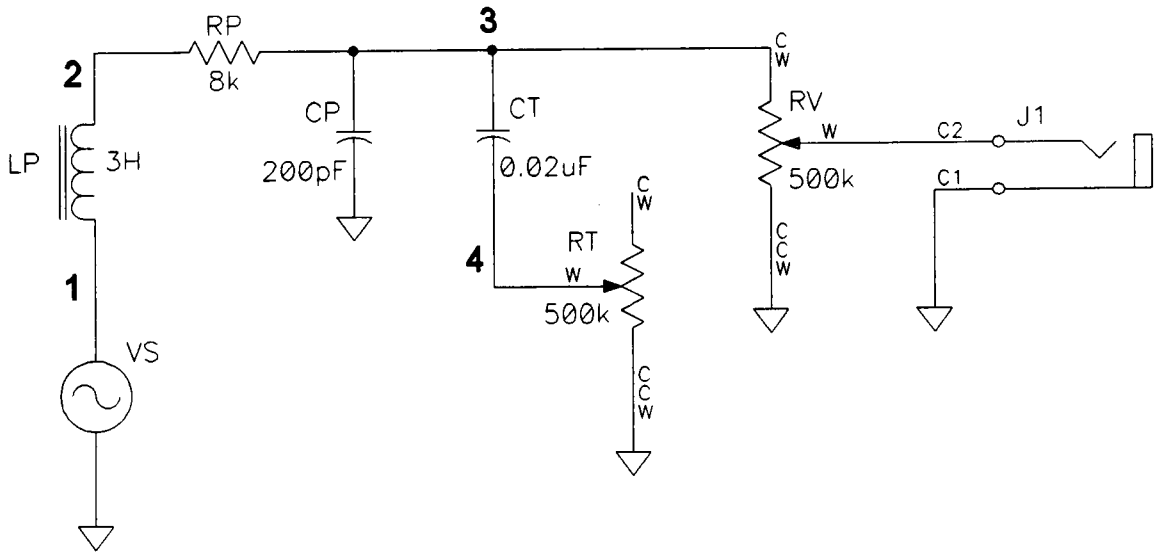



Figure 3.3.5 Magnetic Pickup with Passive Volume and Tone Control.

In order to design a programmable tone control it is important to fully understand the typical guitar tone control system in both the frequency and time domain. This will allow a quantitative comparison to be made with the design of the programmable filter. The node numbers shown in Figure 3.3.5 were used in the circuit PSPICE analysis (a listing of the PSPICE circuit description is given in the Appendix). Here, it is assumed that there is no loading at the output of the volume control Rv. For this reason, Vout will simply be an attenuated version of V(3). The voltage transfer from Vs to V(3) is given by

$$\frac{V(3)}{V_S} = \frac{Z_{Cp} \| Z_T \| R_v}{(Z_{Cp} \| Z_T \| R_v) + R_P + Z_{Lp}} \quad . \tag{3.3.4}$$

By hand analysis, Equation 3.3.4 yields

$$\frac{V(3)}{V_S} = \frac{1 + s R_T C_T}{s^3 a + s^2 b + s c + \left(1 + \frac{R_P}{R_V}\right)} \quad . \tag{3.3.5}$$

Here,

$$a = L_P C_P C_T R_T \quad , \tag{3.3.6}$$

$$b = R_T R_P C_T C_P + L_P C_P + L_P C_T + \frac{L_P C_T R_T}{R_V} \quad , \tag{3.3.7}$$

and

$$c = R_T C_T + R_P C_P + R_P C_T + \frac{R_T R_P C_T}{R_V} + \frac{L_P}{R_V} \quad . \tag{3.3.8}$$

Using MathCad (MathCad, 1992), Equation 3.3.5 was repeatedly solved for the pole and zero locations as $R_T$ was varied from 50 kohm to 500 kohm in 50 kohm steps. This was used to produce the locus of the complete response equation roots versus $R_T$, which is plotted in Figure 3.3.6. Note that the filter characteristic is not fixed, going from a heavily peaked second order response when $R_T$ is 500 kohm, to a nearly Butterworth response when $R_T$ is 50 kohm. Note also that the roots move less and less as $R_T$ is increased. In the limit, as $R_T$ approaches infinity, the root locations are those that would be found if $R_T$ and $C_T$ were not in the circuit. The pole and zero near the origin essentially cancel each other out. As $R_T$ is increased this pole zero pair moves closer and closer together while moving toward the origin. Thus, the system response remains essentially a second order response for all values of $R_T$.

The frequency response of Equation 3.3.5 is plotted in Figure 3.3.7. The response of the passive tone control was also analyzed using PSPICE for several values of $R_T$. Figure 3.3.8 shows the PSPICE frequency response versus $R_T$, while Figure 3.3.9 shows the PSPICE predicted step response versus $R_T$. The PSPICE listing for this circuit can be found in the Appendix. Note that with the passive tone

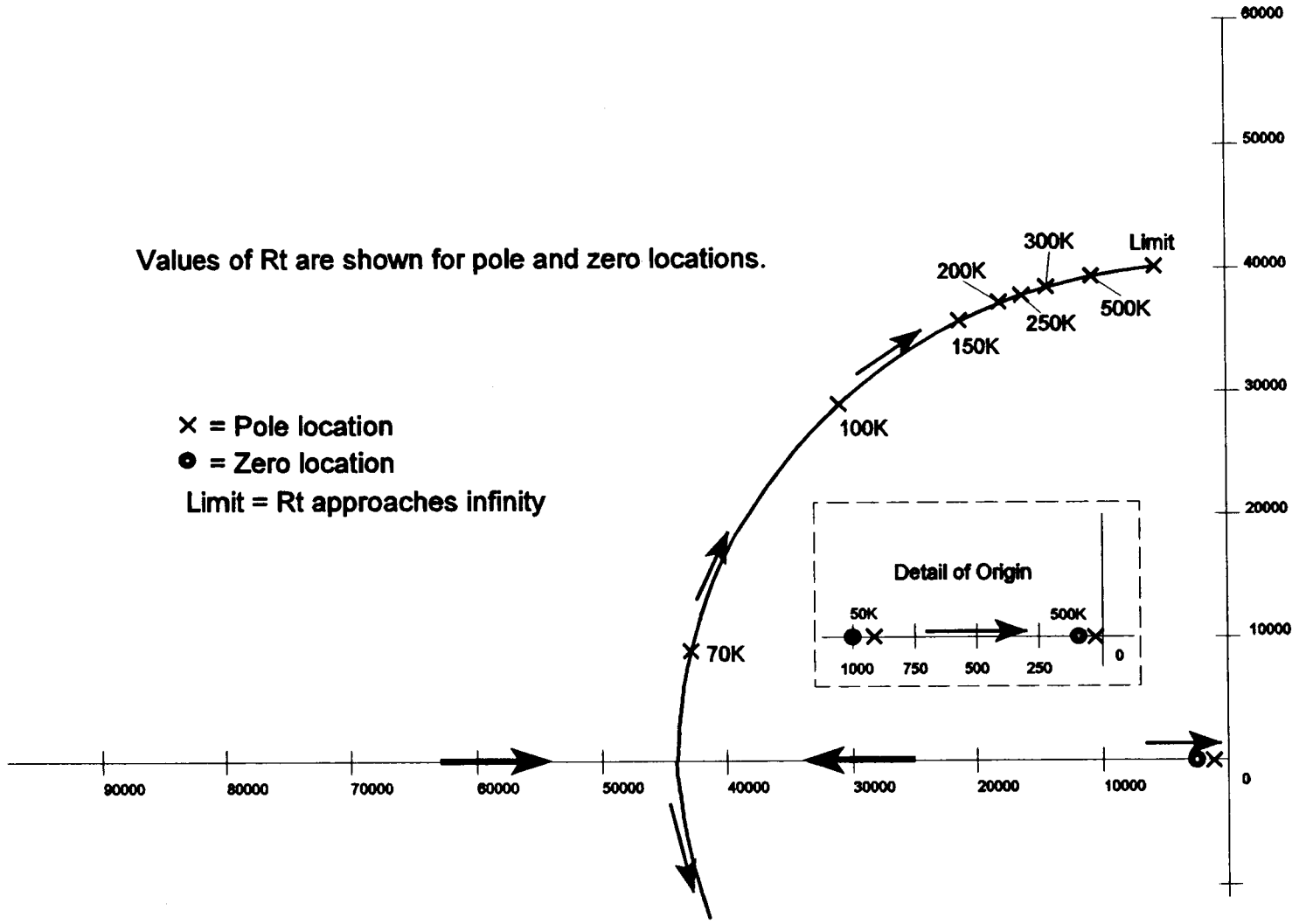
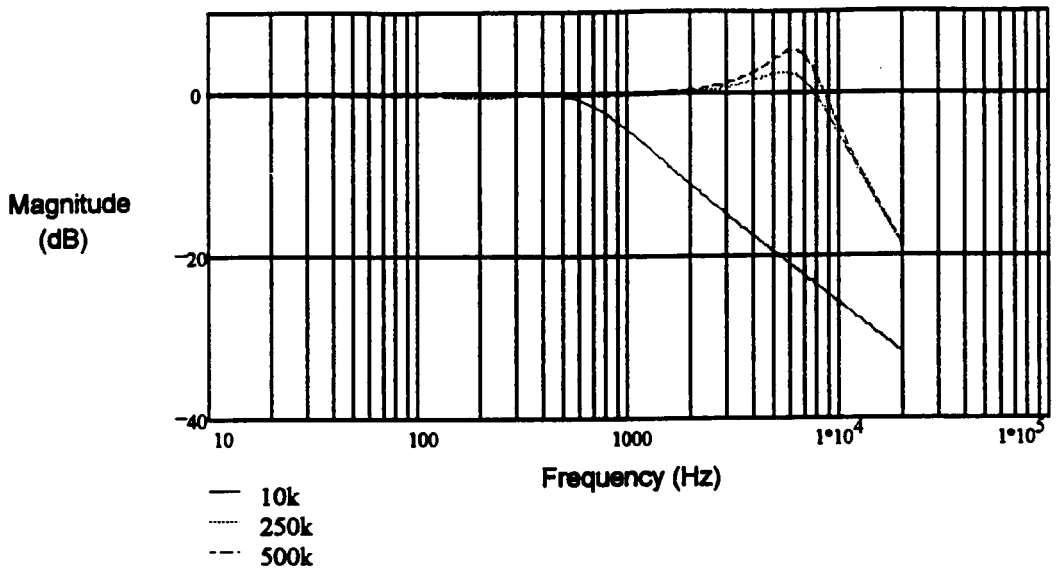
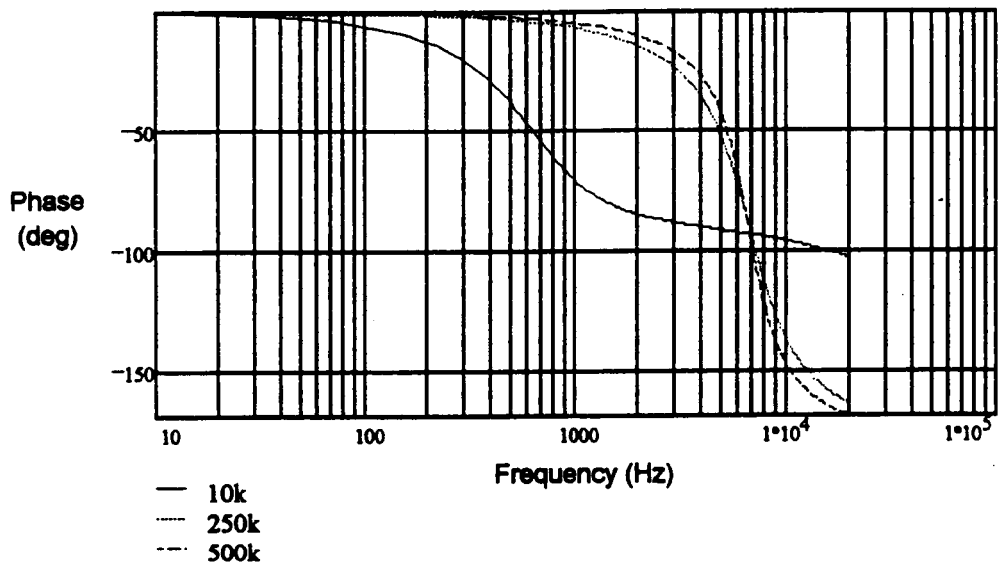



Figure 3.3.6 Root Locus for the Passive Tone Control Circuit versus $R_T$.




(a)




(b)

Figure 3.3.7 Passive Tone Control Frequency Response versus $R_t$.

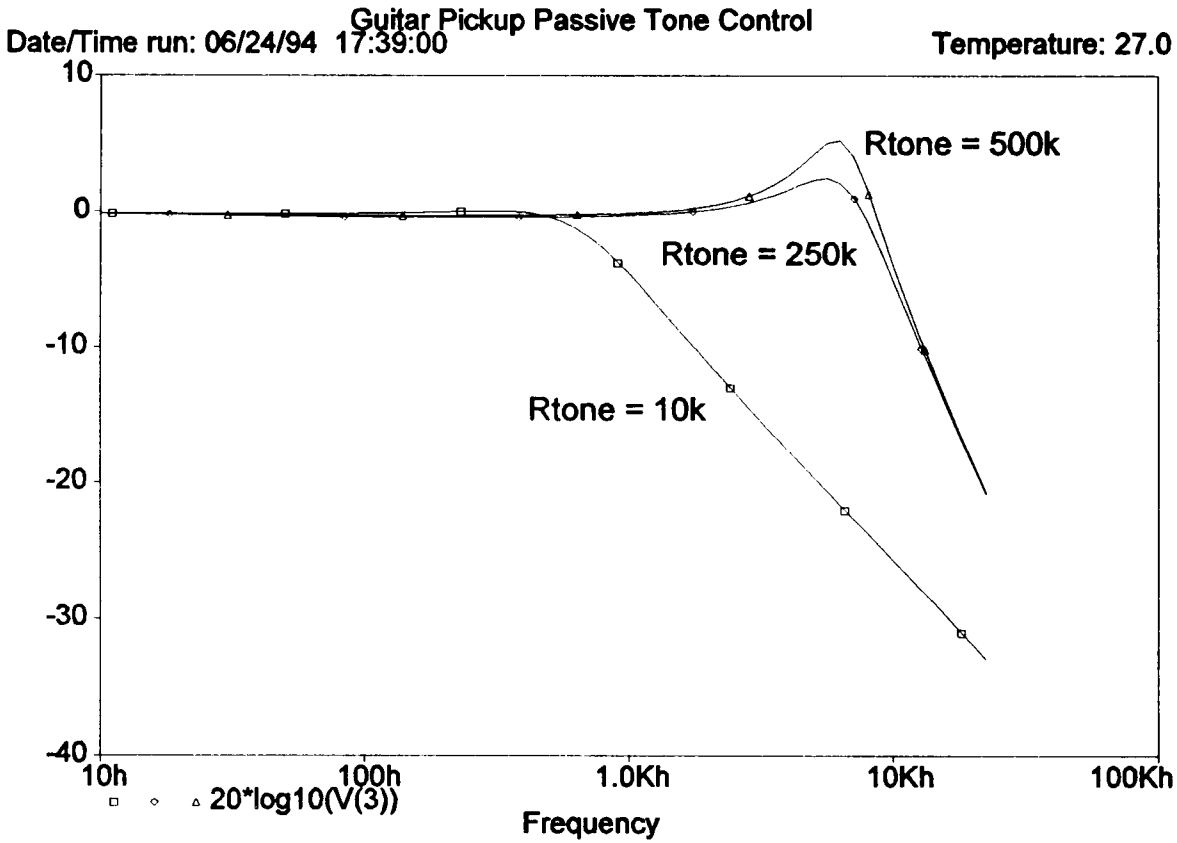



Figure 3.3.8 Frequency Response of the Passive Tone Control as Predicted by PSPICE.

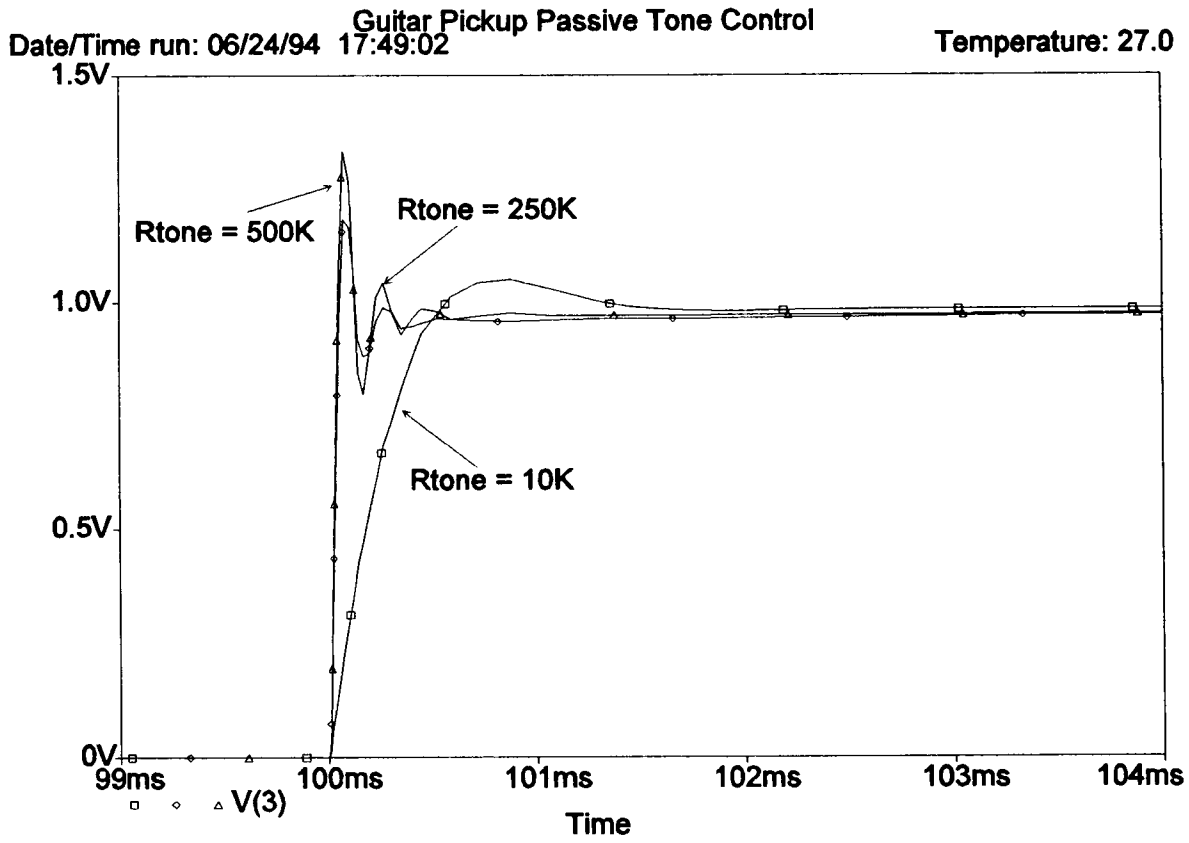



Figure 3.3.9 Transient Response of the Passive Tone Control as Predicted by PSPICE.

control circuit, the pickup response is less peaked near its resonance and has a much shorter settling time after a transient than for the unloaded pickup response. The information gained in this analysis will be used in designing and evaluating the active, programmable tone control circuit for the pickup.

### 3.4 Noise Analysis

To better understand the noise characteristics of the magnetic pickup, the circuit of Figure 3.4.1 was analyzed. Here, the pickup output voltage is buffered by a unity gain follower with equivalent input noise voltage $e_n$ and equivalent input noise current $i_n$. Data for the Texas Instruments TL074 will be used for evaluating the noise performance. The pickup noise, $e_{Rp}$, is produced by the resistance, $R_p$, of the coil wire used in the pickup. The total noise power spectral density at the input of the amplifier (output of the pickup) is (Rochelle, 1993 and Wintenberg, 1989)

$$S_{ototal} = S_{e_n}\left|A_{e_n}\right|^2 + S_{i_n}\left|A_{i_n}\right|^2 + S_{R_p}\left|A_{R_p}\right|^2 , \qquad (3.4.1)$$

where $S_{e_n}$, $S_{i_n}$, and $S_{R_p}$ are the power spectral densities and $A_e$, $A_i$, and $A_{R_p}$ are the gains for $e_n$, $i_n$, and $e_{Rp}$, respectively.

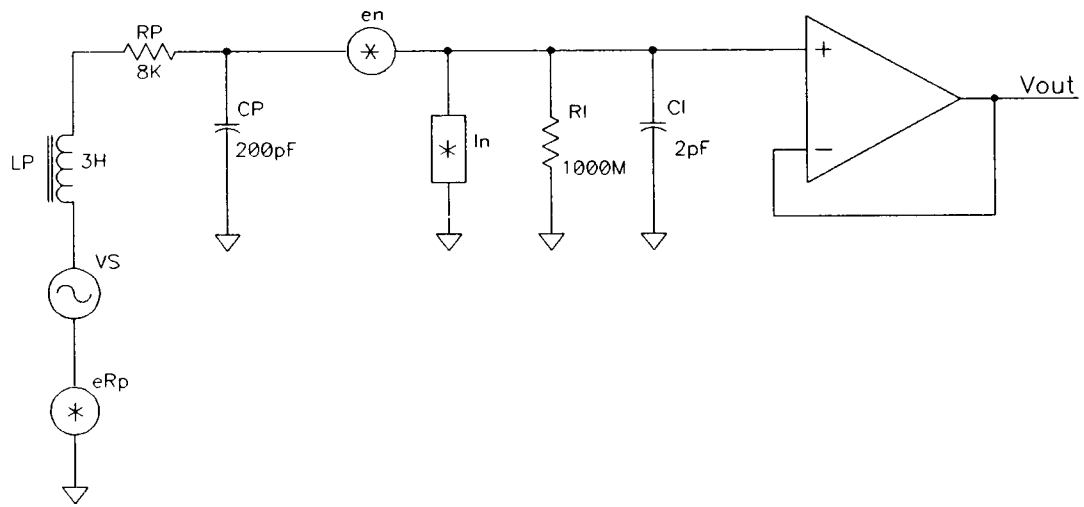



Figure 3.4.1 Circuit Used to Analyze the Magnetic Pickup Equivalent Noise.

The power spectral densities are

$$S_{e_n} = [e_n]^2 \ , \tag{3.4.2}$$

$$S_{i_n} = [i_n]^2 \ , \tag{3.4.3}$$

and

$$S_{R_p} = 4kTR_p \ . \tag{3.4.4}$$

In Equation 3.4.4, k is Boltzmann's constant (1.381 x $10^{-23}$ J/K) and T is the temperature in degrees K (300 degrees K will be used). Note that the op-amp noise contributions are assumed to be white. This will cause some error at frequencies below 300 Hz (the voltage noise corner for the TL074) but will greatly simplify evaluation of the noise. For the TL074 op-amp used in this design, these are

$$e_n = 18 \frac{nV}{\sqrt{Hz}} \quad \text{and} \quad i_n = 0.01 \frac{pA}{\sqrt{Hz}} \ .$$

The magnitude squared gains for each source are now computed.

For $e_n$

$$A_{e_n} = \frac{1}{1 + \frac{Z_p}{Z_i}} \ . \tag{3.4.5}$$

In Equation 3.4.5, $Z_p$ is the pickup impedance and $Z_i$ is the amplifier input impedance. In the bandwidth being considered here, $Z_p << Z_i$ (for the TL074, $Z_i$ is $10^{12}$ ohms), giving $|A_{e_n}|^2 = 1$.

For $i_n$

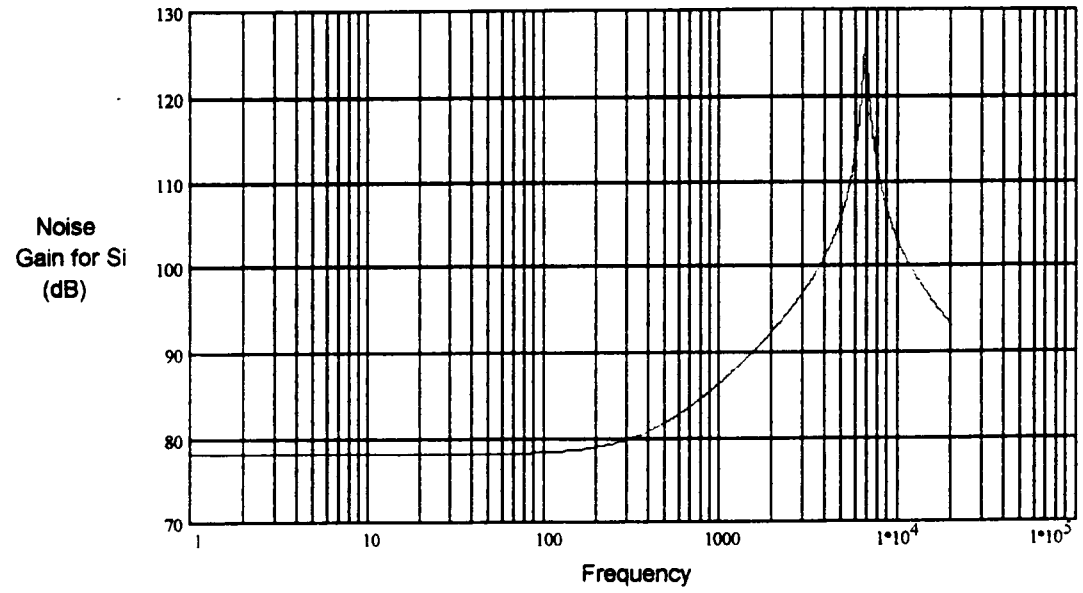
$$|A_{i_n}(f)|^2 = \frac{R_p^2 + (2\pi f L_p)^2}{(2\pi f)^4 (L_p C_p)^2 + (2\pi f R_p C_p)^2 - [2(2\pi f)^2 L_p C_p] + 1}, \qquad (3.4.6)$$

and for $R_p$

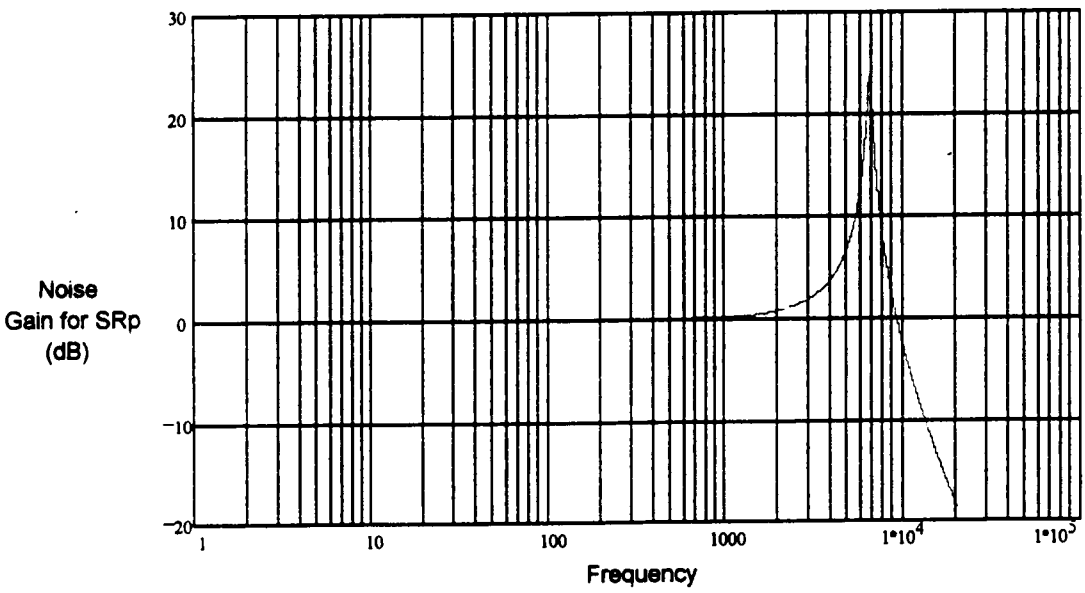
$$|A_{R_p}|^2 = \frac{1}{(2\pi f)^4 (L_p C_p)^2 + (2\pi f R_p C_p)^2 - [2(2\pi f)^2 L_p C_p] + 1}. \qquad (3.4.7)$$

Equations 3.4.6 and 3.4.7 are plotted in Figure 3.4.2. Note that both of these noise power gains are heavily peaked near the magnetic pickup resonance.

The total output noise of Equation 3.4.1 can now be evaluated and is shown in Figure 3.4.3. In Figure 3.4.4, the signal power spectrum for Vs, where Vs was assumed to be 1 mV, is compared to the total noise power as a function of frequency. Vs here is the emf of the magnetic pickup. With typical pickup output voltages of tens of millivolts, this represents a conservative noise evaluation. Since Vs is normally composed of a number of sine components, Figure 3.4.4 (a) can be used to infer the spot noise relationship of the signal to the noise as a function of frequency.




(a)




(b)

Figure 3.4.2 Magnitude Squared Gain for $i_n$ (a) and $R_p$ (b) versus Frequency.

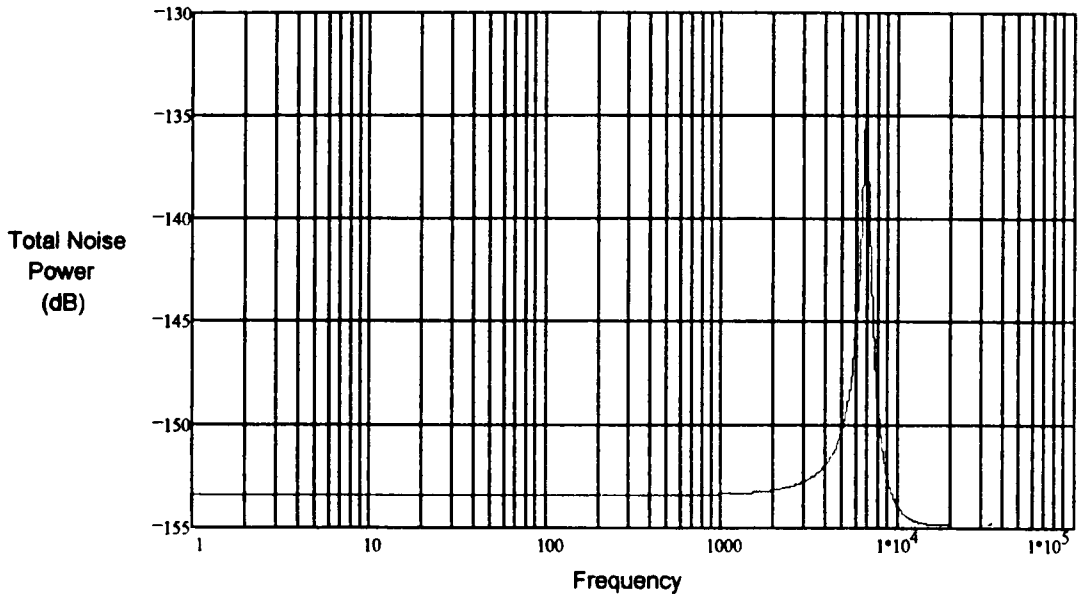
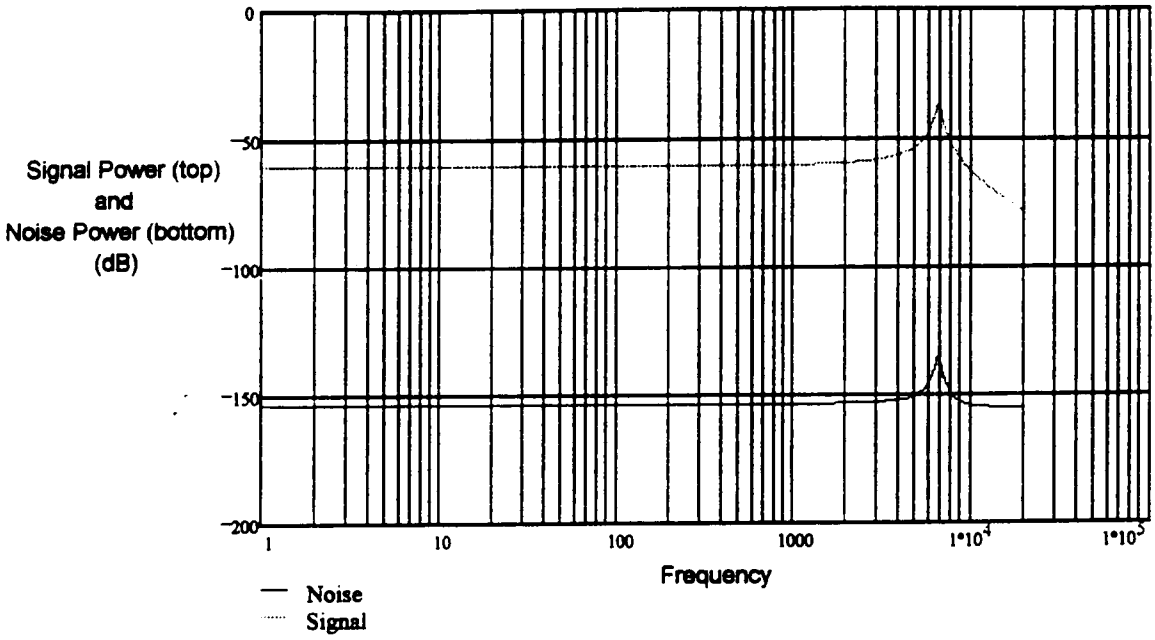
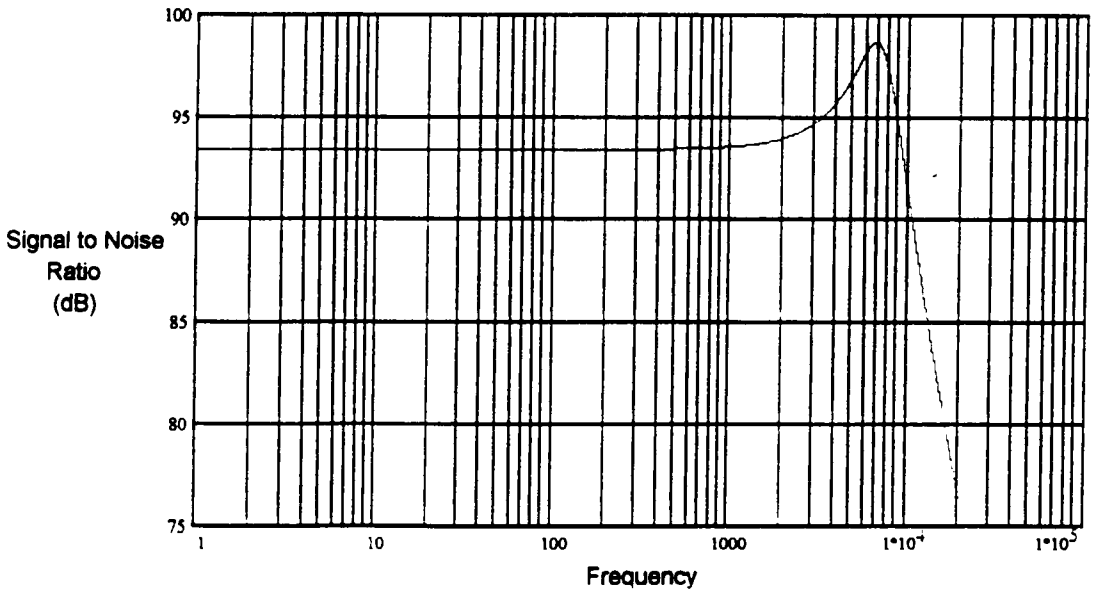



Figure 3.4.3 Total Output Noise Power Spectral Density of the Magnetic Pickup with a Unity Gain Buffer versus Frequency.




(a)




(b)

Figure 3.4.4 Signal Power Spectrum (for a 1 mV Signal) and Noise Power Spectrum (a) and the Power Signal to Noise Ratio (b) versus Frequency.

Figure 3.4.4 (b) shows the power signal to noise ratio. Here the worst case signal to noise ratio is 77 dB at a frequency of roughly 20 kHz (the top ot the audio frequency range). Thus, the random electronic noise is usually negligible.

### 3.5 Alternate Pickup Designs

As mentioned in previous sections, magnetic pickups are susceptible to unwanted interference. Stray magnetic and electrostatic fields from nearby electrical devices both pose a problem for the standard magnetic pickup. Electrostatic fields can be dealt with by applying a non-ferromagnetic shield (which has no effect on the magnetic performance of the pickup) that surrounds the pickup coil assembly. Proper grounding of both the guitar and shielding of the guitar control cavity, along with the avoidance of ground loops in signal processing equipment, will all lessen the likelihood that unwanted electrostatic interference will occur.

Interference from stray magnetic fields is not as readily dealt with. Since the pickup can only work if a large stray magnetic field exists in the vicinity of the guitar's strings, magnetic shielding can only be employed at the side and base of the pickup. Stray magnetic fields in the vicinity of the strings will be sensed along with string motion. Ballast transformers in fluorescent lighting fixtures and the large power transformers found in guitar amplifiers are two major sources of stray field signals.

In the late 1950's (Brosnac, 1983) Seth Lover developed a new pickup configuration which he dubbed the "humbucking" pickup. The pickup design is shown in Figure 3.5.1. Many variations of this design have been used over the years, but all rely on the same basic principle of operation. Here two coils are employed, each located at opposite magnetic poles. The coils are oriented such that the magnetic field lines from the permanent magnet are in opposite directions for each coil. That is to say, the coils will produce voltages that are 180 degrees out of phase for any string motion. Any stray magnetic field that cuts the two coils will produce in phase voltages in the coils (since this external field is oriented the same for each coil). If the coils are connected in series or parallel, with their leads reversed (as shown in Figure 3.5.1 (b) and (c)), then any string motion signal will be enhanced (since the signals are now in phase). Any signal produced by an external field will be eliminated (since these signals are added out of phase). The choice of parallel or series connection is made based on the pickup output voltage and tonal properties desired. Parallel connection (Brosnac, 1983) tends to produce a lower output voltage with more high frequency content (bright, clear treble). Series connection produces a higher output voltage with more low frequency content (bassier sound).

In addition to humbucking pickups, there are several other noteworthy pickup designs currently being marketed. A number of manufacturers now make humbucking pickups in a stacked coil configuration. This allows the pickup to be

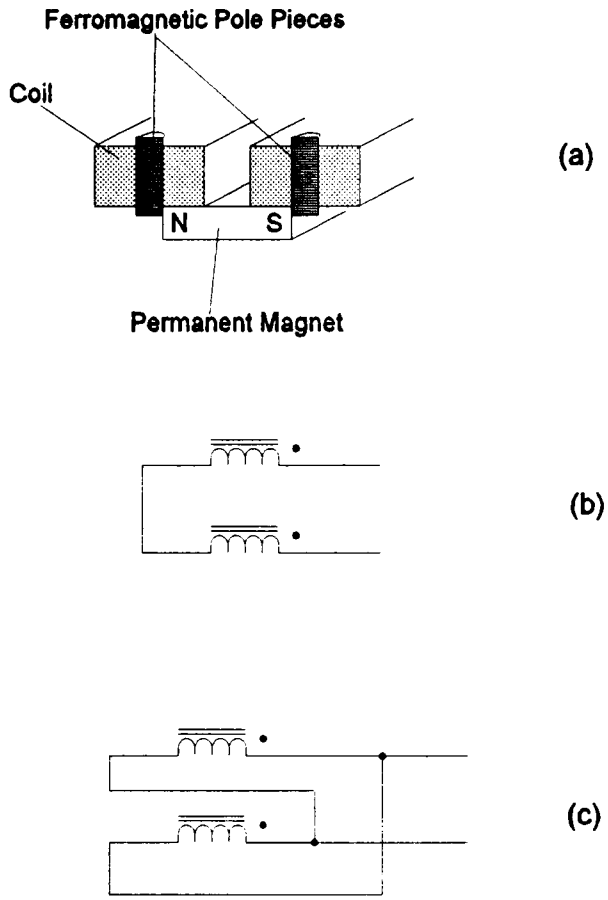



Figure 3.5.1 The Humbucking Pickup.

made in a narrower single coil format. This is important since many guitar body designs only accept the narrower single coil pickup size.

Another design variation (Lace, 1987) is to use a ferromagnetic bobbin assembly with appropriately located fingers in the vicinity of the guitar's strings. These fingers concentrate the flux leaving the top of the pickup near the string improving the efficiency (voltage out per string velocity) of the pickup.

Finally, for guitarists who like to bend strings (this is done to dynamically change the vibrational pitch), "rail" pickups have been developed. As the name implies, these pickups have a ferromagnetic rail that runs perpendicular to the string orientation and couples all of the poles of the pickup together. On a conventional pickup bending a string can lower the pickup's output voltage slightly since the string is moved away from the pickup magnetic pole (concentrated flux region).

# 4. THE GUITAR CONTROL SYSTEM CIRCUIT DESIGN

## 4.1 Overview

There are six main sections to the electric guitar control system. Figure 4.1.1 shows a block diagram of the control system. The design described here is based on a guitar with two dual coil humbucking pickups, a single volume control, and a single tone control. Provision is made for selecting either pickup and also provides two opposing phase modes.

The battery power system is based on a DC to DC converter which provides +5 volts and -4 volts from a pair of AA batteries. The battery power system is described in Section 4.2.

The pickup switching function is performed using CMOS analog transmission gates which are compatible with the available power supply. The pickup switching circuit is described in Section 4.3.

The system microcontroller is not specified in this design. Section 4.4 provides an outline of the microcontroller requirements. An outline of the firmware needed to operate the microcontroller is provided in Section 5.

The Volume/Tone system is based on an active op-amp filter circuit where the circuit response is controlled using a digital to analog converter (DAC). Section 4.5 describes this circuit.

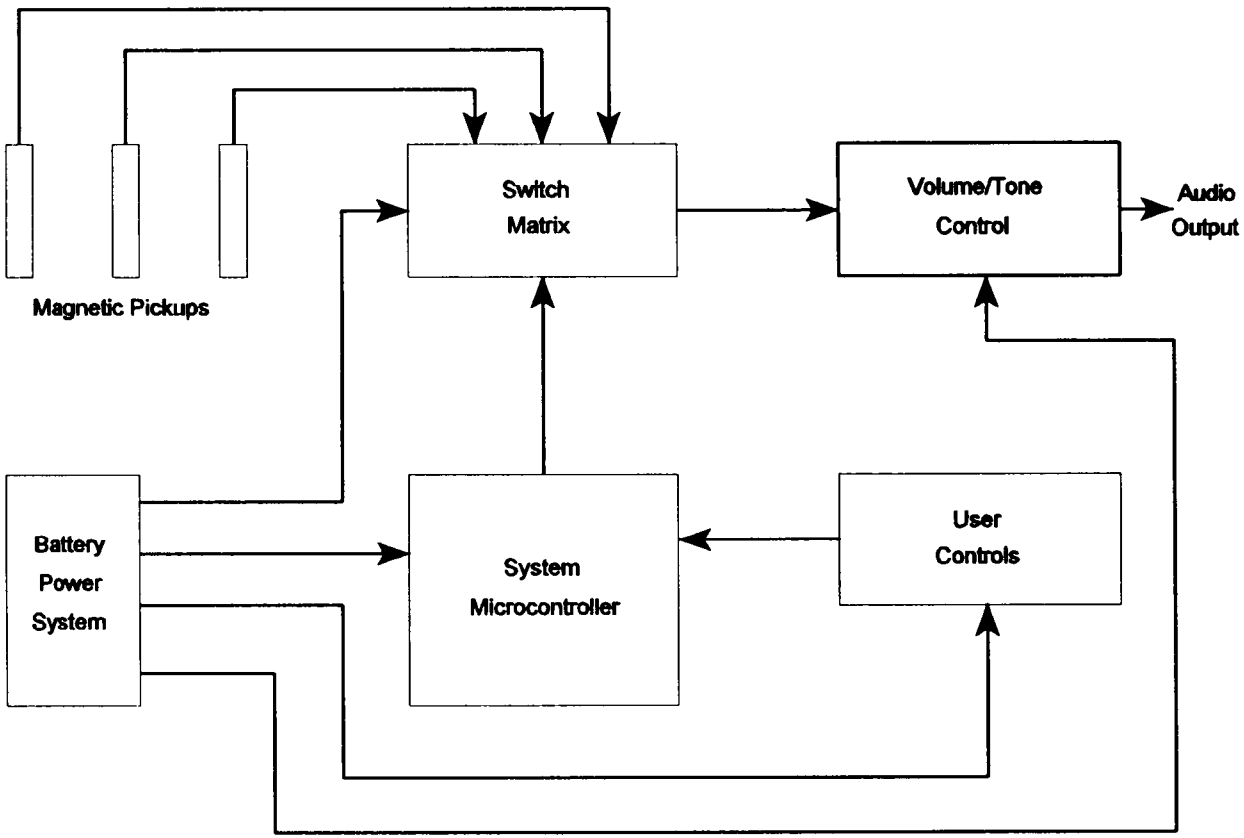



Figure 4.1.1 Guitar Control System Block Diagram.

The user controls are designed to resemble, as much as possible, the normal control set up found on an electric guitar. Section 4.6 outlines the control requirements for this design.

The magnetic pickups were discussed in detail in Section 3 and are not discussed here.

## 4.2 The Battery Power System

Two types of batteries were considered for use in the battery power circuit. These are AA and 9V style batteries. Table 4.2.1 shows a comparison of these two battery types.

In the system, either two AA cells or one 9V cell would be used. To compare the two battery options, energy capacity is computed as:

$$Energy_{9V} = (550\,mA\,Hr)(9\,V)\,3600\,\frac{sec}{Hr} = 17.8\,kJ \quad , \tag{4.2.1}$$

and

$$Energy_{2\text{-}AA} = (2100\,mA\,Hr)(3\,V)\,3600\,\frac{sec}{Hr} = 22.7\,kJ \quad . \tag{4.2.2}$$

Table 4.2.1. Comparison of 9V and AA Style Batteries.

| Size | Dimensions (mm) | Volume ($cm^3$) | Capacity (mAHr) | Weight (g) | Nominal Voltage (V) | Cutoff Voltage (V) |
|---|---|---|---|---|---|---|
| 9V | 26.2L x 48.4H x 16.8W | 21 | 550 | 57.1 | 9 | 4.8 |
| AA | 14.2Dia x 50.0H | 7.4 | 2100 | 21.0 | 1.5 | 0.8 |
| | | | | | | |

Data Taken From Duracell, Incorporated Data Sheet, August, 1986

This assumes that current is delivered from the battery with no change in cell output voltage (a poor assumption for alkaline batteries, but sufficient for a rough comparison of performance). Note that there is a moderate difference in available energy between the AA and 9 volt batteries with 2 AA batteries providing more energy. Given the advantages of lower cost, lighter weight, smaller volume and greater energy, two AA batteries operating in series will be used in this design.

Since the system microcontroller requires a 5 volt supply to operate, it is desirable that all the electronics be able to operate with only a single 5 volt supply. In order to provide regulated 5 volts for the circuitry independent of the widely varying battery output, a step up type of DC to DC switching regulator is required. A number of simple switching regulators designed to operate with 3 volt inputs are currently available. The author has chosen a Maxim Semiconductor MAX-631 for this design. This chip requires very few external components, provides capability to produce a negative bias supply, and has a low battery voltage warning output. The MAX-631 oscillator operates at roughly 50 kHz, well outside the audio spectrum, which is important in avoiding coupling of unwanted switching supply noise into the signal processing path. Figure 4.2.1 shows the DC to DC converter schematic. The most critical component of the design is $L_x$, which must be properly sized to provide good regulation of the output and to prevent damage to the switching transistor on board the MAX-631.

Following Maxim's (Maxim, 1992) design procedure, the acceptable range of values for $L_x$ is found by considering the limiting conditions for inductor size.

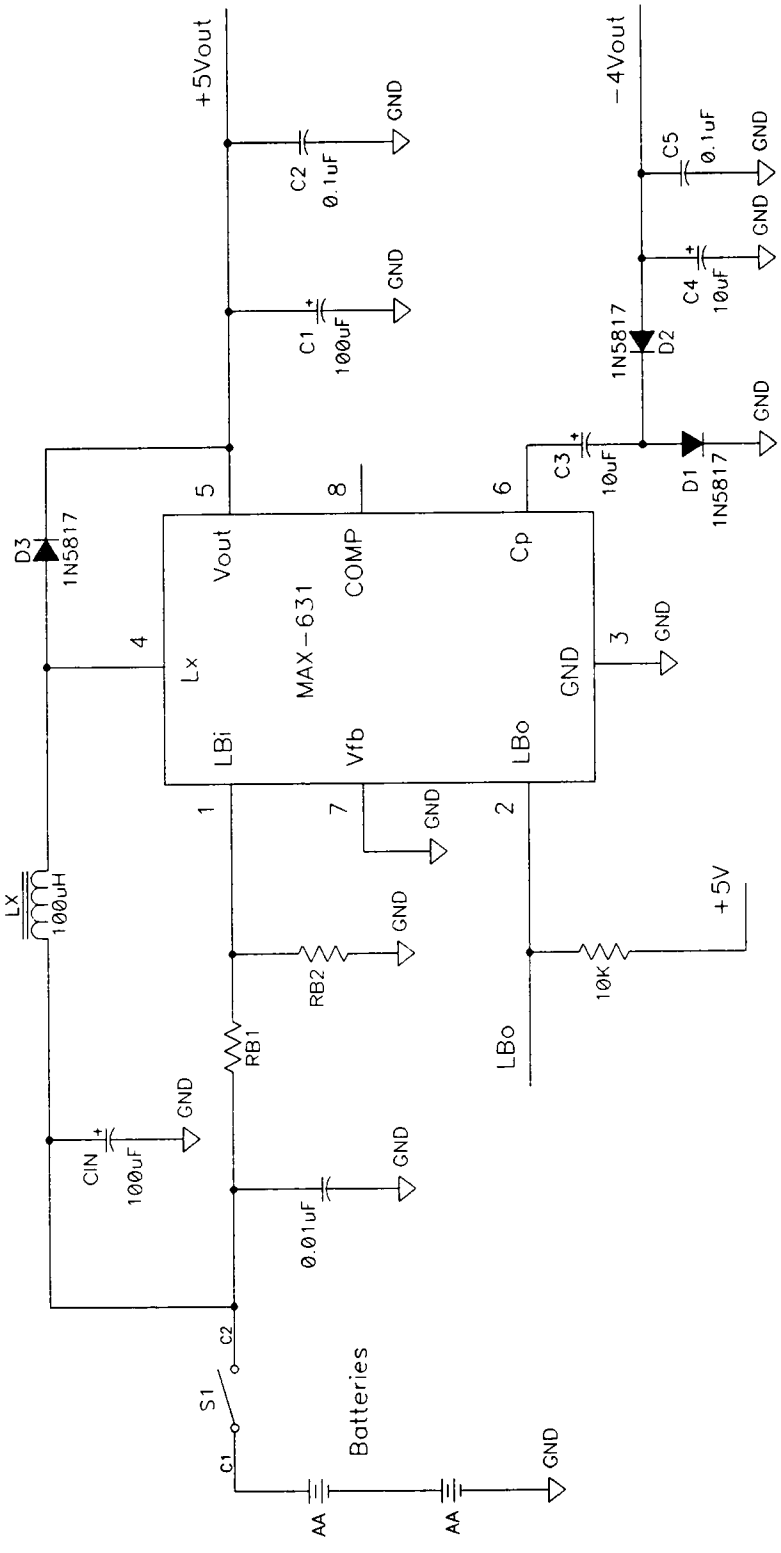



Figure 4.2.1 The DC to DC Converter Schematic.

The minimum value of inductance is found using the MAX-631 switch transistor maximum current rating. When the MAX-631 switch is active, the battery input is connected to the load through $L_x$. The current through $L_x$ rises in a linear fashion while the output switch is on, limited only by the value of $L_x$, the battery voltage, and the switch on time. The output switch maximum on time is given as 12 microseconds. Since the MAX-631 output switch is limited to 450 milliamps, the minimum acceptable value of $L_x$ is found by considering the maximum peak current, the maximum switch on time, the maximum battery voltage, and the minimum switch on voltage, or

$$L_x(\min) = \frac{V_b\max - V_{sw}\min}{I_{lim}} T_{on}\max = \frac{3 - 0.25}{450\,mA} 12\,\mu s = 73\,\mu H \quad . \qquad (4.2.1)$$

The maximum acceptable value of $L_x$ is found by considering the minimum peak current, the minimum switch on time, the minimum battery voltage, and the maximum switch on voltage. Here $L_x$ is

$$L_x(\max) = \frac{V_b\min - V_{sw}\max}{I_{pk}\min} T_{on}\min \quad . \qquad (4.2.2)$$

Since $I_{pk}$ is given by

$$I_{pk}\min = \frac{V_{out} + V_d - V_b\max}{V_{sw}\min(V_{out} - V_{sw}\max)} I_{out} \quad , \qquad (4.2.3)$$

then $L_x$ maximum is

$$L_x \max = \frac{(1.8 - 0.75)}{2.26\, I_{out}} 8\,\mu s = 186\,\mu H \quad . \tag{4.3.3}$$

for $I_{out}$ = 20 milliamps (which is the nominal current drain expected for the circuit).

$L_x$ was built using an Amidon Associates T68-3 toroid core. This is a low frequency mix, iron-powder core. The toroidal configuration is desirable to minimize stray magnetic coupling of power supply energy to the magnetic pickup on the guitar. This particular core, while not the best choice for a switching power supply design, was used due to availability.

The low battery warning trip point, $V_{lb}$, is set to 1.8 volts (200 millivolts above the battery fully discharged point) by $R_{b1}$ and $R_{b2}$ as

$$R_{b1} = R_{b2}\left(\frac{V_{lb}}{1.3} - 1\right) = 0.374\, R_{b2} \quad . \tag{4.3.4}$$

Output from the $V_{lb}$ bit will be passed to the microcontroller which will, in turn, flash a low battery indicator LED.

A low current negative output rail is provided using the MAX-631 charge pump output in conjunction with three capacitors (C3, C4 and C5) and two Schottky diodes (D1 and D2). This is not a low impedance supply and will be used only to provide a negative rail for the Volume/Tone control op-amps. The Schottky diodes

are used to provide the maximum possible negative output voltage (which is roughly -4 volts).

Schottky diode D3 is wired in parallel to the internal clamp diode for the main switch transistor. D3 improves the efficiency of the converter slightly by providing better clamp characteristics and faster turn on and turn off (due to the lower storage time for the Schottky diode).

Filtering for the output of the converter is provided by C1 and C2. C1 must be a low ESR (equivalent series resistance) electrolytic capacitor to minimize the amount of ripple at the switcher switching frequency. C2 is used to provide additional bypassing for high frequency noise in the supply output.

The efficiency of the switcher will be influenced by the design of $L_x$, the input voltage, and the output load current. The MAX-631 data sheet indicates that the efficiency should be on the order of 75%.

### 4.3 Pickup Switching

The mechanical switching system found on a typical guitar is replaced in this system by a digitally controlled analog switch matrix. The switches employed are standard CMOS analog switches arrayed to implement the desired switch functions. Figure 4.3.1 shows a schematic of the pickup switch system. The CMOS switches were chosen since they are readily available and can operate from a single rail, +5 volt supply.

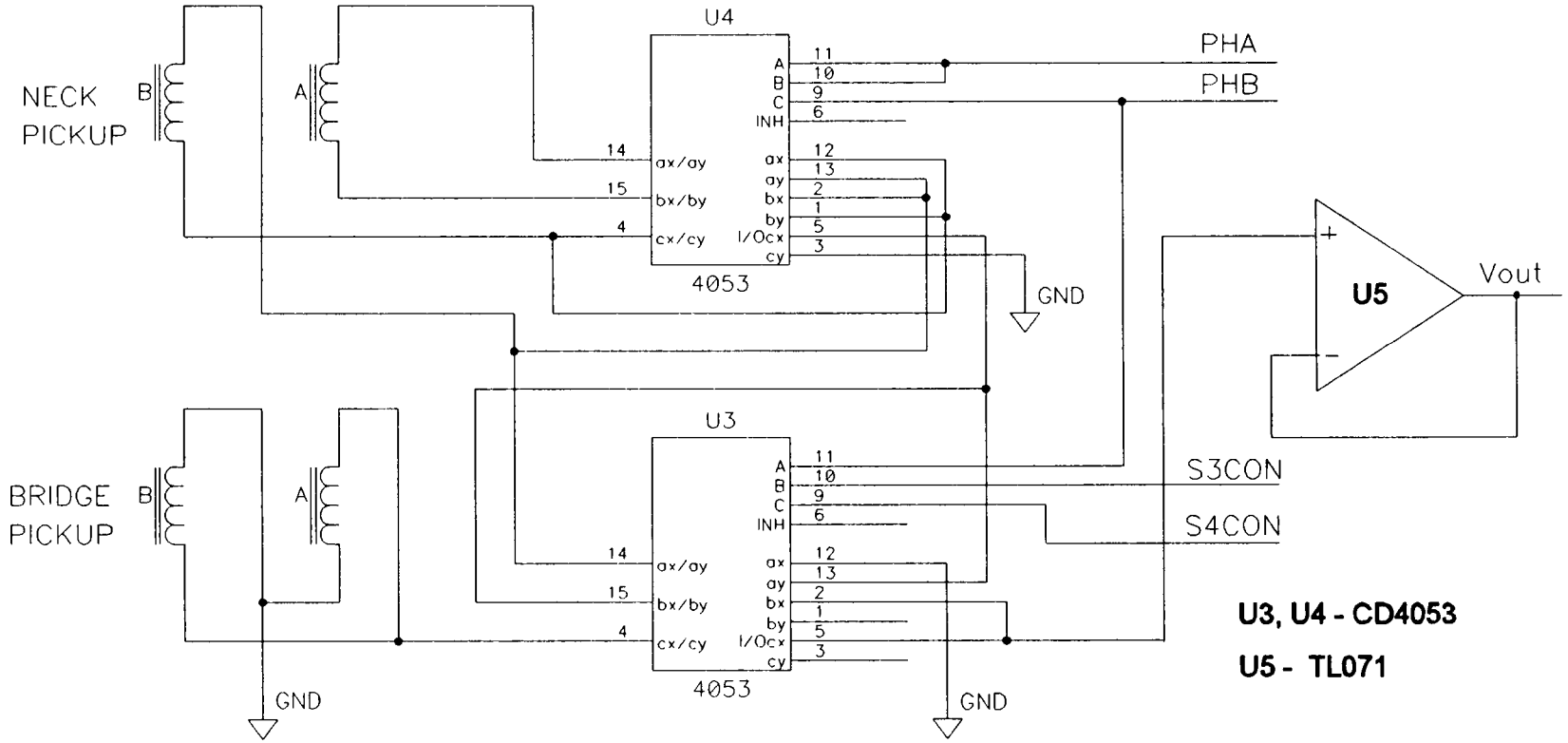



Figure 4.3.1 Pickup Switch Matrix Schematic.

There are six modes of operation for the switch matrix. Table 4.3.1 lists each mode and the data required to drive the switches for that mode. The switches were arranged to minimize the number of control lines required from the microcontroller. Latches are employed to hold the switch configuration data allowing these lines to be used in controlling other parts of the guitar control system.

## 4.4 System Microcontroller

The heart to the electric guitar electronic control system is the system microcontroller. The guitar control circuits were designed with an 8-bit, low cost microcontroller IC in mind. A number of microcontrollers on the market could be used in this system. An analog input (with an integral 8-bit A/D convertor) is needed to process the control signals from the tone and volume potentiometers. Roughly 13 to 20 digital I/O lines are needed to control the switch matrix and Volume/Tone controls. To make the system robust an internal watchdog timer is recommended.

The microcontroller's job is to read the state of the control inputs and drive the volume/tone and pickup selection controls appropriately. The standard resistive controls found on a typical guitar are used here to produce analog voltage outputs which are read by the analog inputs of the microcontroller. All switch control positions are encoded as an 8-bit code which is also passed to the microcontroller.

Table 4.3.1. Switch Matrix Mode Listing.

| Mode | PHA | PHB | S3CON | S4CON | Pickup Selections |
|---|---|---|---|---|---|
| 1 | X | X | 1 | 0 | Bridge Only |
| 2 | 0 | 0 | 0 | 0 | Bridge and Neck (normal) |
| 3 | 0 | 1 | 0 | 0 | Bridge and Neck (Phase Reversed) |
| 4 | 1 | 0 | 0 | 0 | Bridge and Neck (Phase Reversed in Neck) |
| 5 | 0 | X | 0 | 1 | Neck Only |
| 6 | 1 | X | 0 | 1 | Neck Only (Phase Reversed in Neck) |

X = Don't Care
0 = Logic Low State
1 = Logic High State

A block diagram of the microcontroller circuit is given in Figure 4.4.1. The microcontroller circuit should be located as far away from the pickups and switch matrix as possible since microprocessors tend to produce unwanted high frequency clock noise.

## 4.5 Volume/Tone Control

The volume/tone control circuit is comprised of a digitally programmable gain/frequency response filter circuit. The filter response is controlled using several 8-bit digital-to-analog converter (DAC) circuits (R-2R ladders) which would be programmed by the system microcontroller. The microcontroller would program each DAC over an 8-bit parallel data bus. Data for programming the DAC's would be read from the guitar control configuration by the microcontroller.

Before proceeding with the filter design, we will first consider the use of a DAC R-2R ladder in controlling an op-amp circuit gain. Figure 4.5.1 shows a standard inverting gain op-amp configuration where a DAC R-2R ladder has been placed at the amplifier inverting input. The input current to the R-2R ladder is given by

$$I_{in} = \frac{V_{in}}{R_{dac}} \quad , \tag{4.5.1}$$

where $R_{dac}$ is the resistance seen looking into the DAC R-2R ladder.

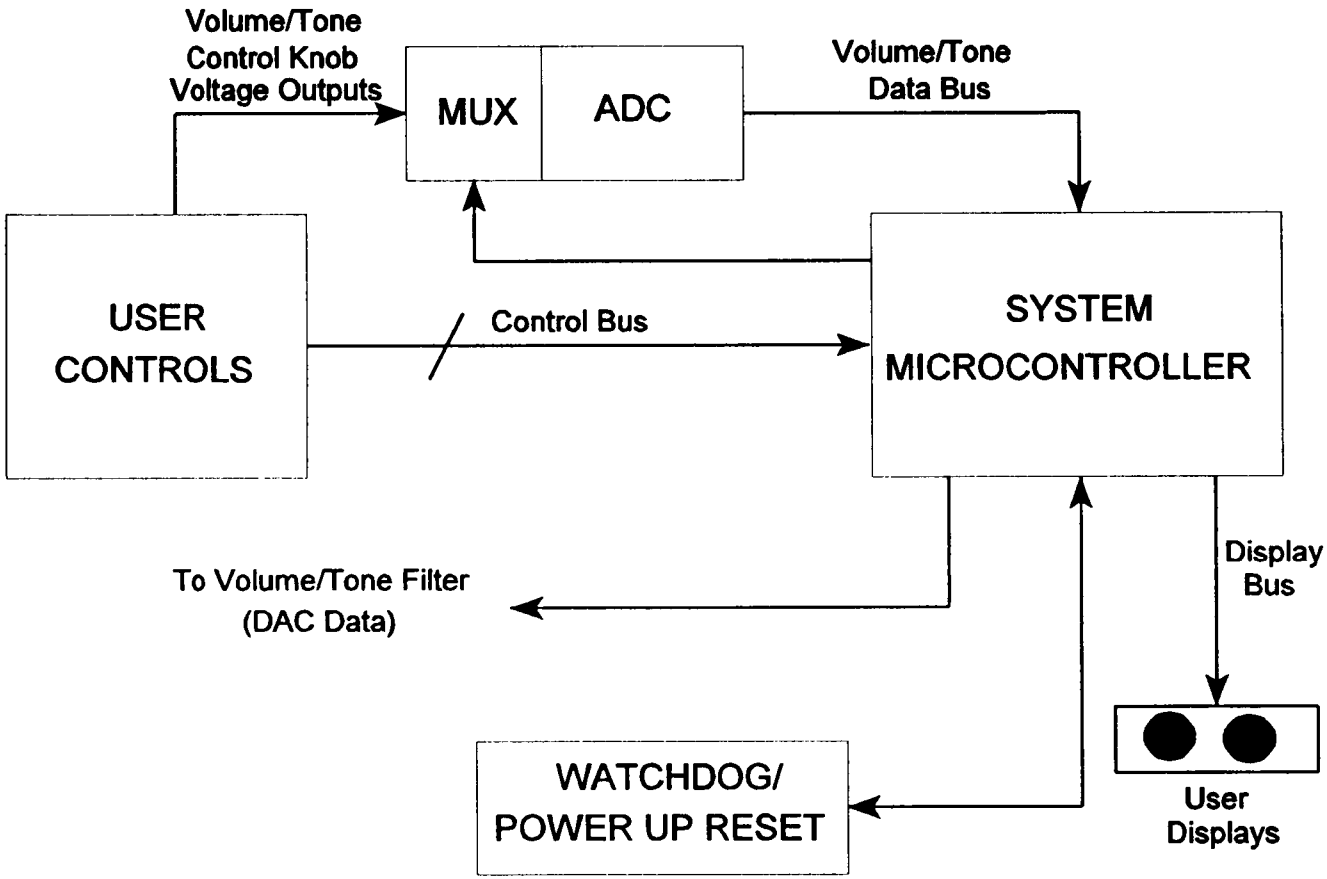



Figure 4.4.1 The System Microcontroller Block Diagram.

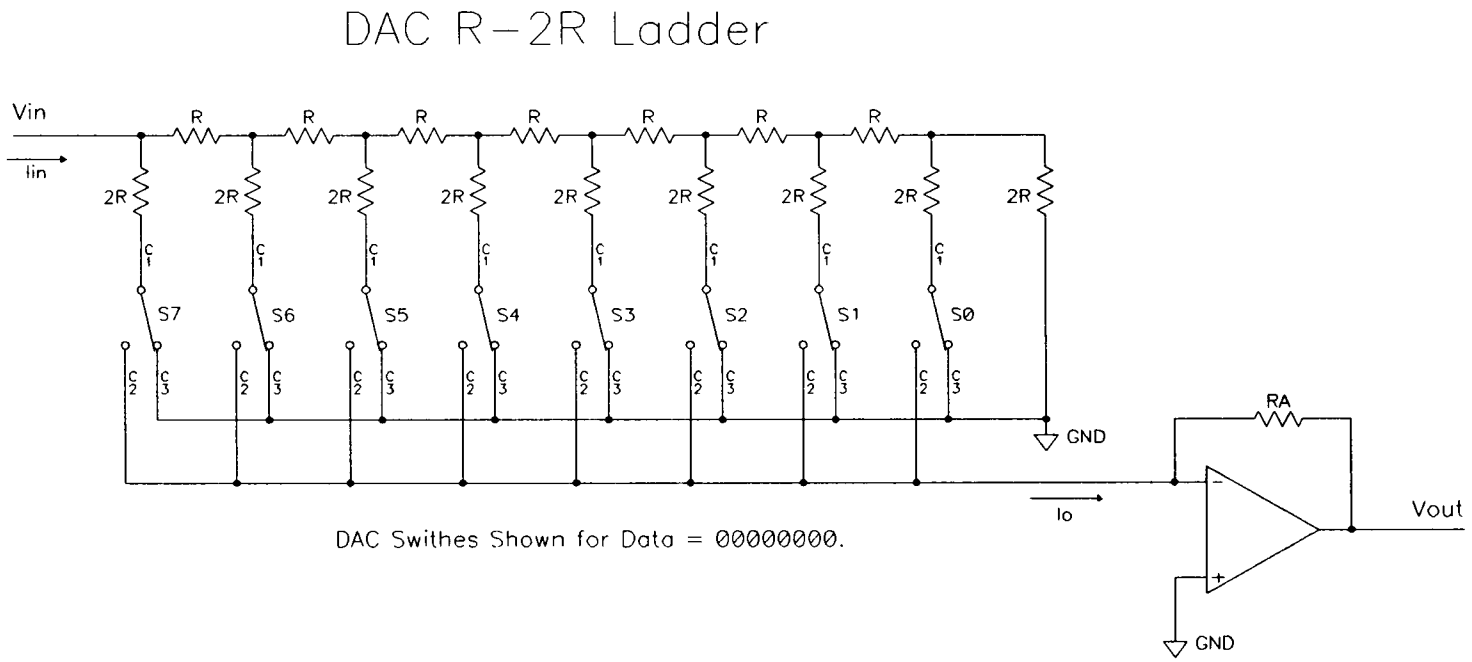



Figure 4.5.1 Inverting Gain Amplifier Controlled by a Digital to Analog Converter R-2R Ladder.

The value of $R_{dac}$ is equal to the standard resistor element value of the R-2R ladder (typical resistance values are 5k to 20k ohms). The amount of current, $I_o$, flowing out of the R-2R network at the op-amp inverting input is determined by the digital code, D (an 8-bit binary number), programmed at the DAC. Here,

$$I_o = \frac{D}{256} I_{in} \quad . \tag{4.5.2}$$

Now the amplifier gain can be computed as

$$\frac{V_o}{V_{in}} = -\frac{R_A}{R_{dac}}\left(\frac{D}{256}\right) \quad . \tag{4.5.3}$$

Thus the amplifier maximum gain is set by $R_A$ and D. The maximum value of D (for an 8-bit DAC) is 255. The minimum gain is equal to zero, at D = 0. The value of $R_{dac}$ remains constant at $V_{in}$ due to the ladder structure of the R-2R network.

Now, consider the circuit of Figure 4.5.1 with $R_A$ replaced by a capacitor, $C_A$, to form a standard inverting integrator circuit. The gain is computed in the complex frequency domain, as

$$\frac{V_o}{V_{in}}(s) = \frac{-1}{s\,(R_{dac}\,C_A)\left(\frac{256}{D}\right)} \quad . \tag{4.5.4}$$

Here, D determines the integrator gain. As D increases, more current is a available to charge $C_A$, increasing the effective integrator gain. At D = 255, the response approaches the normal $R_{dac}$ x $C_A$ integrator gain factor. Note that the value of D must be equal to or greater than one for the circuit to operate properly. When D is equal to 1, the response of the integrator is reduced by a factor of 256. In the time domain, this would correspond to a 256 times longer integration period. Both the variable gain and variable time constant circuits will be used in implementing the volume/tone control circuit.

As shown in Section 3.3, the typical guitar uses a passive single pole RC tone control circuit. To provide a sharper filter cutoff, here a second order filter response will be used. It is desired that the filter response remain constant, except for the cutoff frequency, over the control range. The author has chosen to base the filter design on an active state-variable (SV) filter configuration. The SV filter was chosen for two main reasons. First, the SV filter's cutoff frequency, gain and Q are independently adjustable. Thus, the filter response profile can be scaled in gain or frequency without changing the basic filter characteristics. Secondly, the SV filter can be implemented using all inverting gain amplifiers and integrators (Analog Devices, 1992), which will allow DAC R-2R networks to be used to control the filter response.

Note that a filter circuit that requires varying the resistance at a voltage summing node can be implemented using a DAC R-2R ladder. Here the problem is that, while the DAC R-2R ladder can be used as a variable resistance, the

resistance range is limited and does not follow a binary weighting. This is due to the structure of the R-2R ladder (Sheingold, 1986). Since the system microcontroller will output its control data in binary format, binary weighting of the DAC response will greatly simplify the design.

It is desired that the filter response be as flat as possible in the passband (in order to minimize "coloring" the sound of the pickup). For this reason, a Butterworth (or maximally flat) response will be implemented. For a second order Butterworth filter , the normalized complex frequency response is

$$H(s) = \frac{1}{s^2 + 1.414\,s + 1} \quad , \tag{4.5.5}$$

with characteristic equation roots at

$$roots_{1,2} = -0.7071 \pm j\,0.7071 \quad . \tag{4.5.6}$$

The normalized Butterworth filter Q is 0.7071. Equation 4.5.5 will be used in determining the required circuit values for the SV filter.

The SV filter configuration has been analyzed by both Wait and Kennedy (Wait, 1975 and Kennedy, 1988). Figure 4.5.2 is a simplified schematic for the filter circuit. Note that four DAC resistor ladders will be used in place of the indicated resistors in the filter circuit. Resistors R1 and R2 will be adjusted in tandem to control the filter cutoff frequency. Resistors R3 and R4 are used to set the filter Q

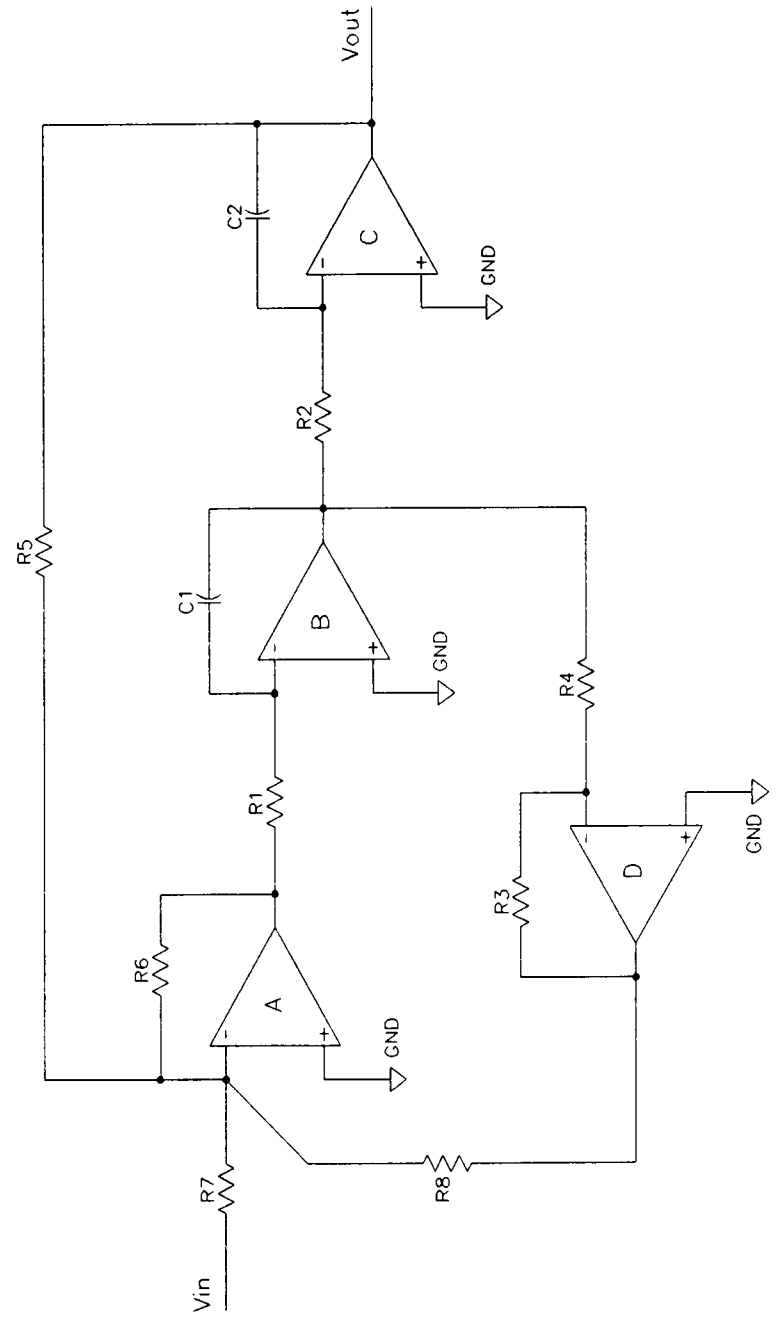



Figure 4.5.2 State-Variable Filter Simplified Schematic.

and are programmed at a fixed value for a specific filter response. R7 sets the filter gain and is used here as the volume control.

For the SV filter, the complex frequency response equation is given as

$$H(s) = \frac{-\left(\frac{1}{R1\,R2\,C1\,C2}\right)^2\left(\frac{R6}{R7}\right)\left(\frac{R6}{R5}\right)}{s^2 + \left(\frac{1}{R1\,C1}\right)\left(\frac{R4}{R3}\right)\left(\frac{R8}{R6}\right)s + \left(\frac{1}{R1\,R2\,C1\,C2}\right)\left(\frac{R6}{R5}\right)} \quad . \tag{4.5.7}$$

H(s) in Equation 4.5.7 can be simplified by letting R1 = R2 = RDAC, R5 = R6 = R8 = RA and C1 = C2 = C. Now, equation 4.5.1 reduces to

$$H(s) = \frac{-\left(\frac{1}{R_{dac}\,C}\right)^2\left(\frac{RA}{R7}\right)}{s^2 + \left(\frac{1}{R_{dac}\,C}\right)\left(\frac{R4}{R3}\right)s + \left(\frac{1}{R_{dac}\,C}\right)^2} \quad . \tag{4.5.8}$$

The ratio RA / R7 determines the filter gain. Since R7 will be actually be an R-2R ladder, R7 is equal to $R_{dac}$. As in Equation 4.5.3, the maximum filter gain is approximately RA / $R_{dac}$ when the digital control code is 255. The minimum gain is then

$$\frac{RA}{256\,R_{dac}} \quad . \tag{4.5.9}$$

The filter Q is, by Equations 4.5.5 and 4.5.8, given by

$$Q = \frac{R3}{R4} \quad . \tag{4.5.10}$$

For the Butterworth filter

$$Q = 0.7071 = \frac{R3}{R4} = \frac{D}{256} \quad , \tag{4.5.11}$$

where R3 and R4 have been replaced by an R-2R DAC resistor ladder. This gives a digital code of $D_Q = 181$.

The DAC being used in this design is an Analog Devices, DAC-8408. The DAC-8408 has a nominal ladder resistance of $R_{dac} = 10$ kohms and provides four separate DAC R-2R ladders. Setting RA to 100 kohms will give the filter a gain range of -0.039 to -10.

It is desired that the filter cut-off range span the audio frequency band (20 Hz to 20 kHz). The maximum cut-off frequency of the filter is given by

$$f_c = \frac{1}{2\pi R_{dac} C \left( \frac{256}{255} \right)} \quad , \tag{4.5.12}$$

or

$$C = \frac{1}{2\pi R_{dac} f_c \left( \frac{256}{255} \right)} = 793\,pF \ , \ \text{with } f_c = 20kHz \quad . \tag{4.5.13}$$

The nearest standard value of capacitance is 820 pF. This gives a tuning range for $f_c$ of 75.5 Hz $\leq f_c \leq$ 19.3 kHz . $R_{dac}$ can vary from 6 kohms to 14 kohms. This will cause the upper and lower tuning limits to be roughly +/- 8 kHz. Thus, it may be necessary to adjust the value of C to compensate for the variation of $R_{dac}$.

In order to isolate the 10 kohm input impedance of the filter circuit, U5 is used as a non-inverting buffer for the magnetic pickup. The complete filter circuit schematic is shown in Figure 4.5.3. Testing of the filter circuit is reported in Section 6.4.

The overall response of the guitar controller and the pickup can now be evaluated. From Equations 3.3.2 and 4.5.8 the total complex frequency response of the electronic control system is

$$H_c(s) = \frac{(2\pi f_o)^2}{s^2 + 2\zeta(2\pi f_o)^2 s + (2\pi f_o)^2} \cdot \frac{-f_{lp}^2\left(\frac{RA\ D_G}{R_{dac}\,256}\right)}{s^2 + f_{lp}\left(\frac{D_Q}{256}\right)s + f_{lp}^2} \quad , \tag{4.5.14}$$

where

$$f_{lp} = \left(\frac{1}{2\pi R_{dac} C \frac{256}{D_f}}\right) \quad . \tag{4.5.15}$$

Here, $D_Q$ = 181 (Butterworth response), $D_G$ is the gain control setting, and $D_f$ is the filter cut-off control setting. This equation has been evaluated for several values of $D_f$ with $D_Q$ = 181 and $D_f$ = 26 (approximately unity gain), with s = j2πf. Figure 4.5.4 shows the filter response as computed using MathCad. PSPICE was also

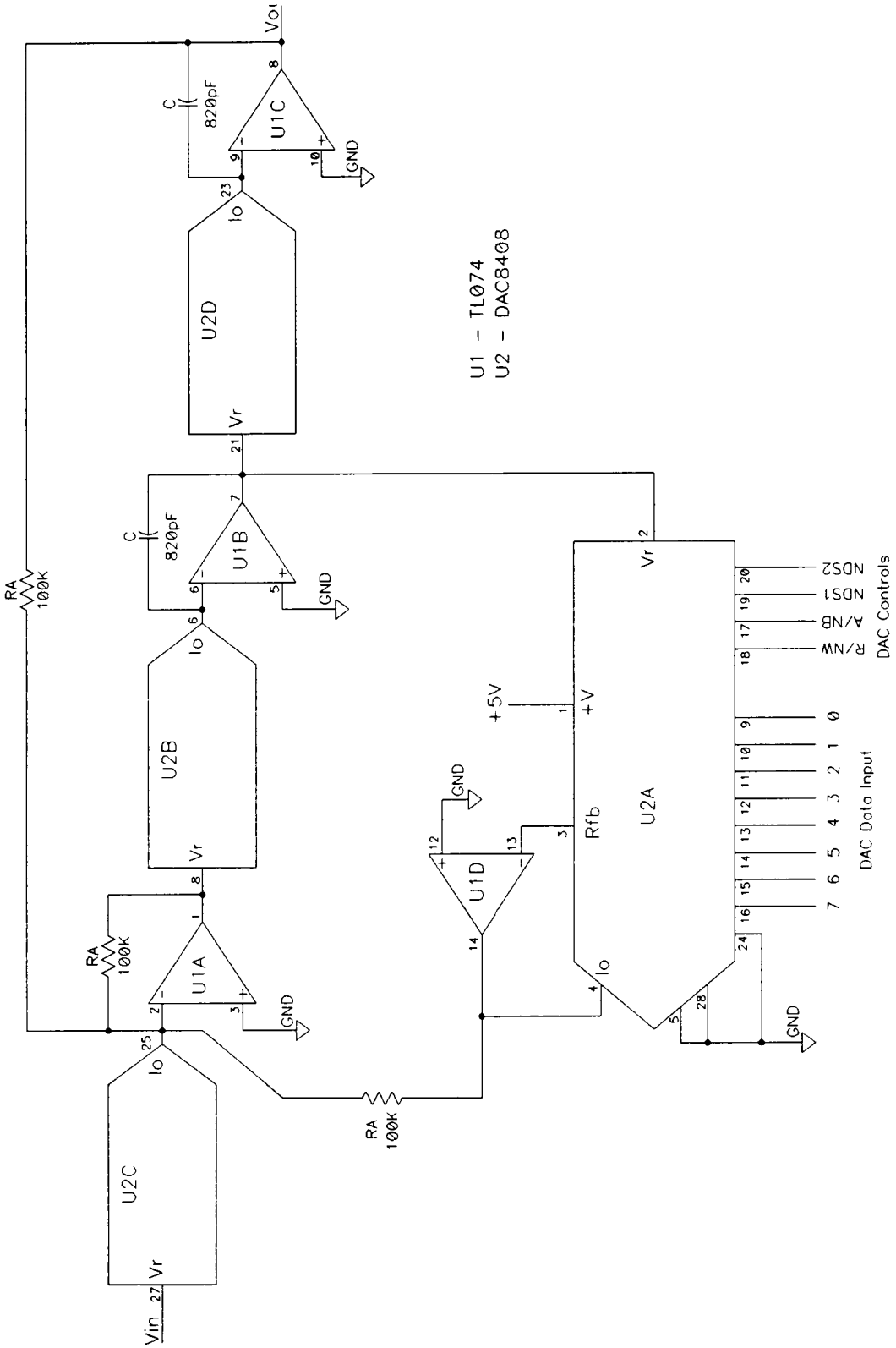



Figure 4.5.3 Volume/Tone Control Circuit Schematic.

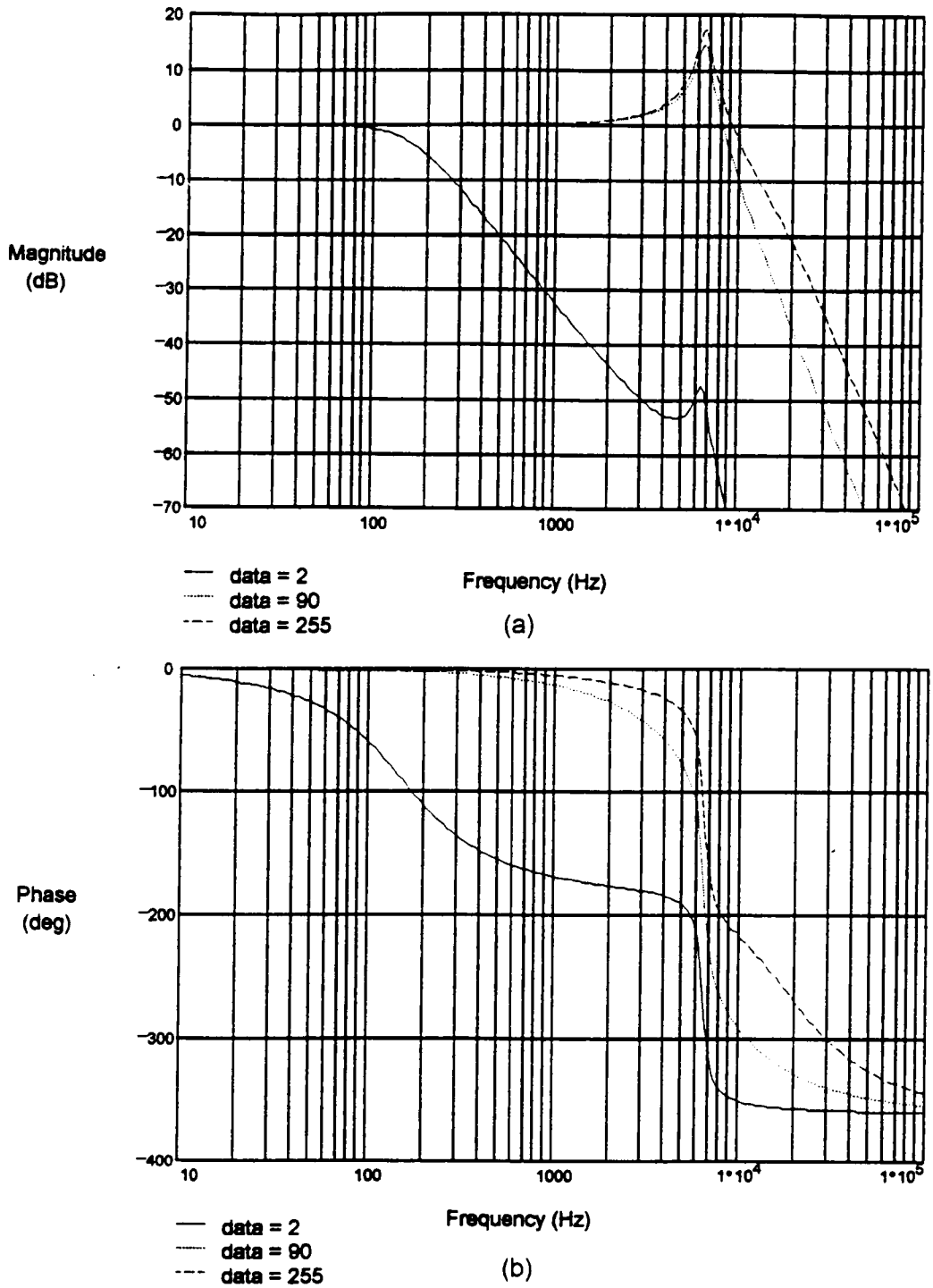



Figure 4.5.4 The Electronic Control System Frequency Response (MathCad).

used to evaluate the circuit performance (using ideal op-amp models) as shown in Figure 4.5.5 for frequency response and Figure 4.5.6 for transient response. The active filter compares favorably with the passive tone control evaluated in Section 3.

### 4.6 User Controls

Even though the user controls will not be realized in hardware form as a part of this effort, it is well worth outlining the structure of such a set of controls. Figure 4.6.1 shows the basic control layout. Two light-emitting-diode (LED) displays are provided. One will flash periodically when the batteries used in the DC to DC converter circuit are nearly discharged (battery Vout < 1.8 volts). The second LED is used in programming the guitar.

Two potentiometers are provided. One is used as a volume control and the other as a tone control. These controls are wired as shown in Figure 4.6.2. The analog output voltages from the controls, which span 0 to 5 volts, are passed to the system microcontroller on-board analog-to-digital converter (ADC). The voltage read by the ADC can then be used to program the volume level and tone setting via the DAC in the volume/tone circuit.

Pickup selection and phase relationships are controlled by three toggle switches. These toggle switches are used as shown in Figure 4.6.1.

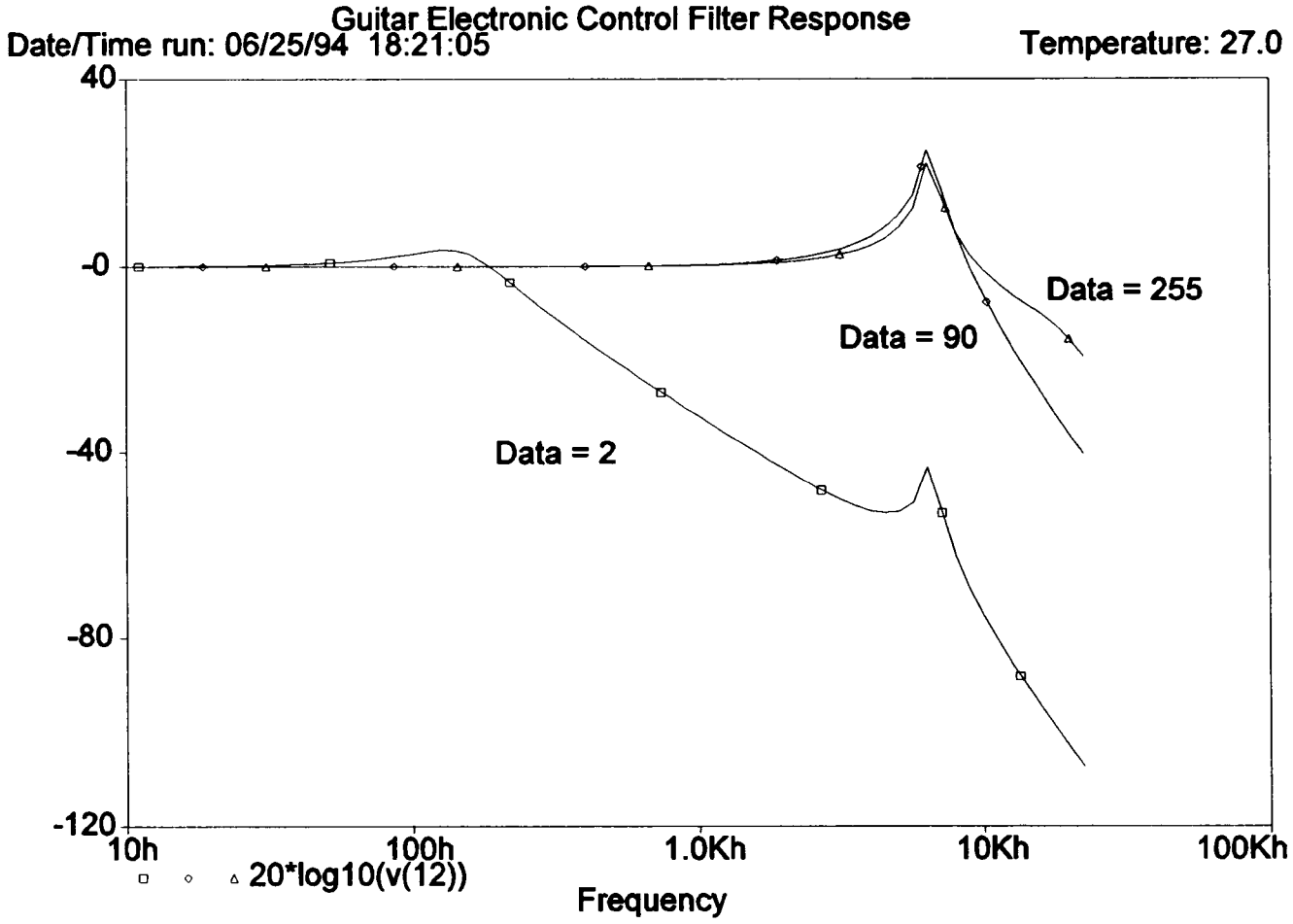



Figure 4.5.5 The Electronic Control System Frequency Response (PSPICE).

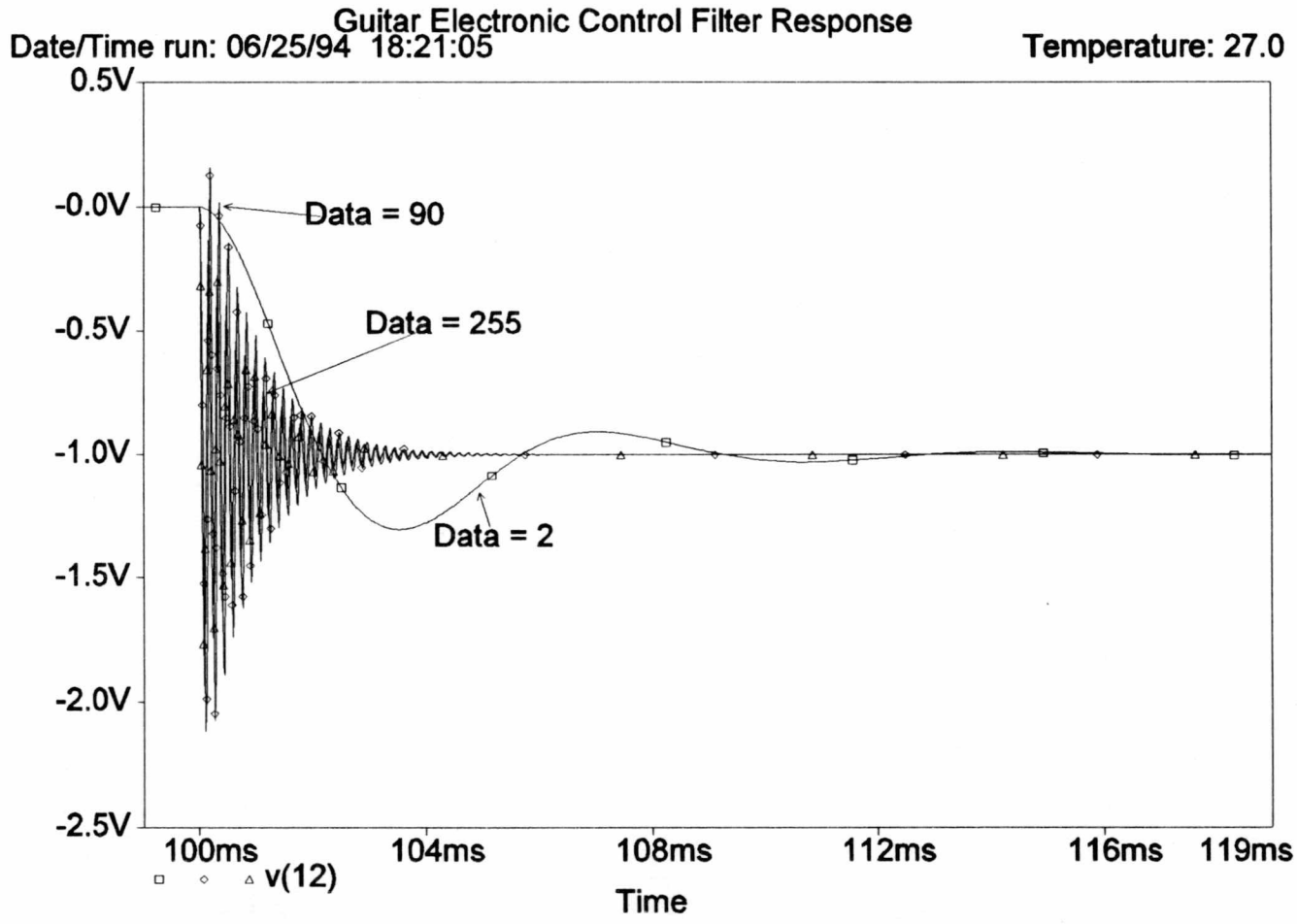



Figure 4.5.6 The Electronic Control System Transient Response (PSPICE).

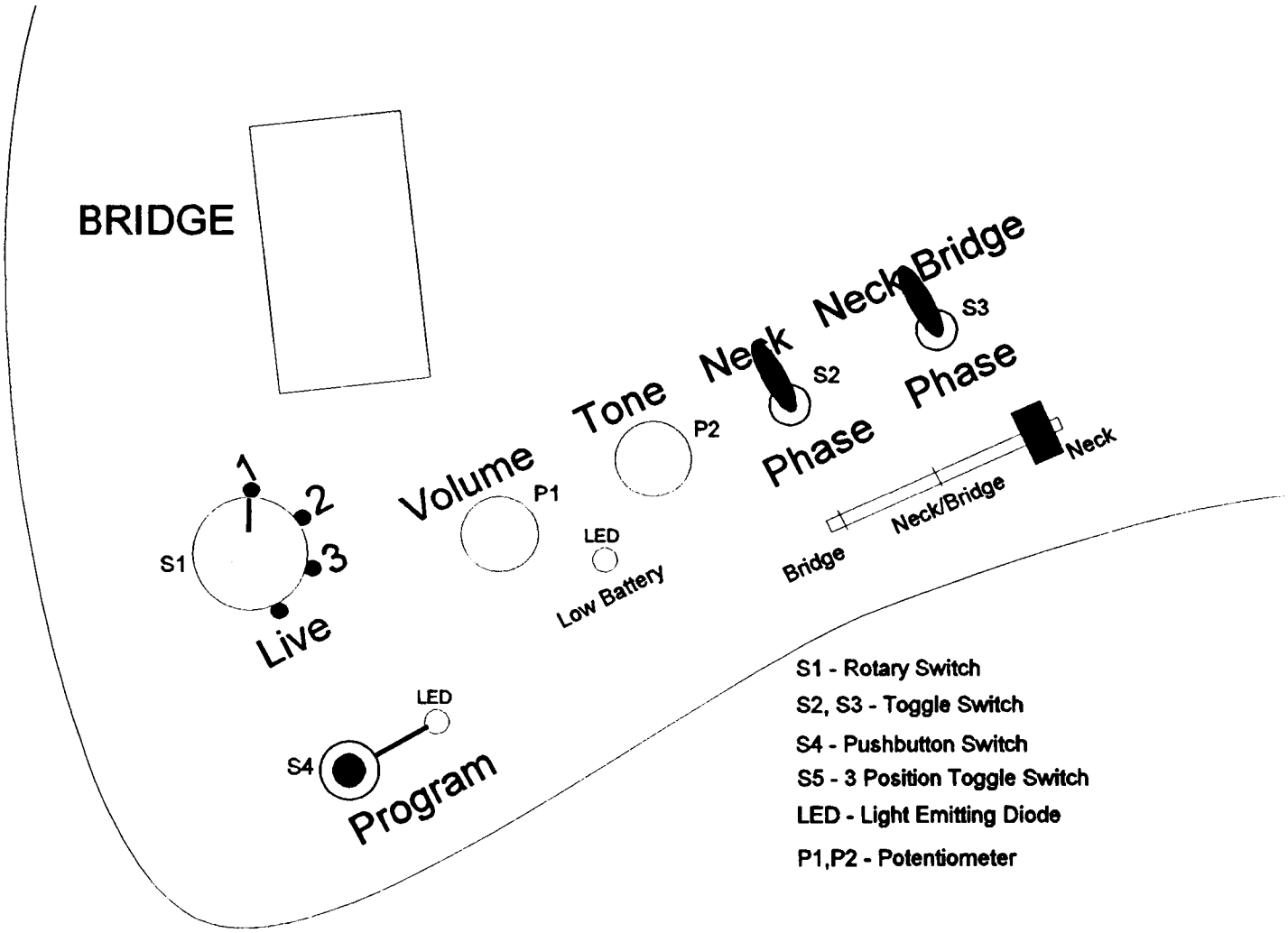



Figure 4.6.1 The User Control Layout.

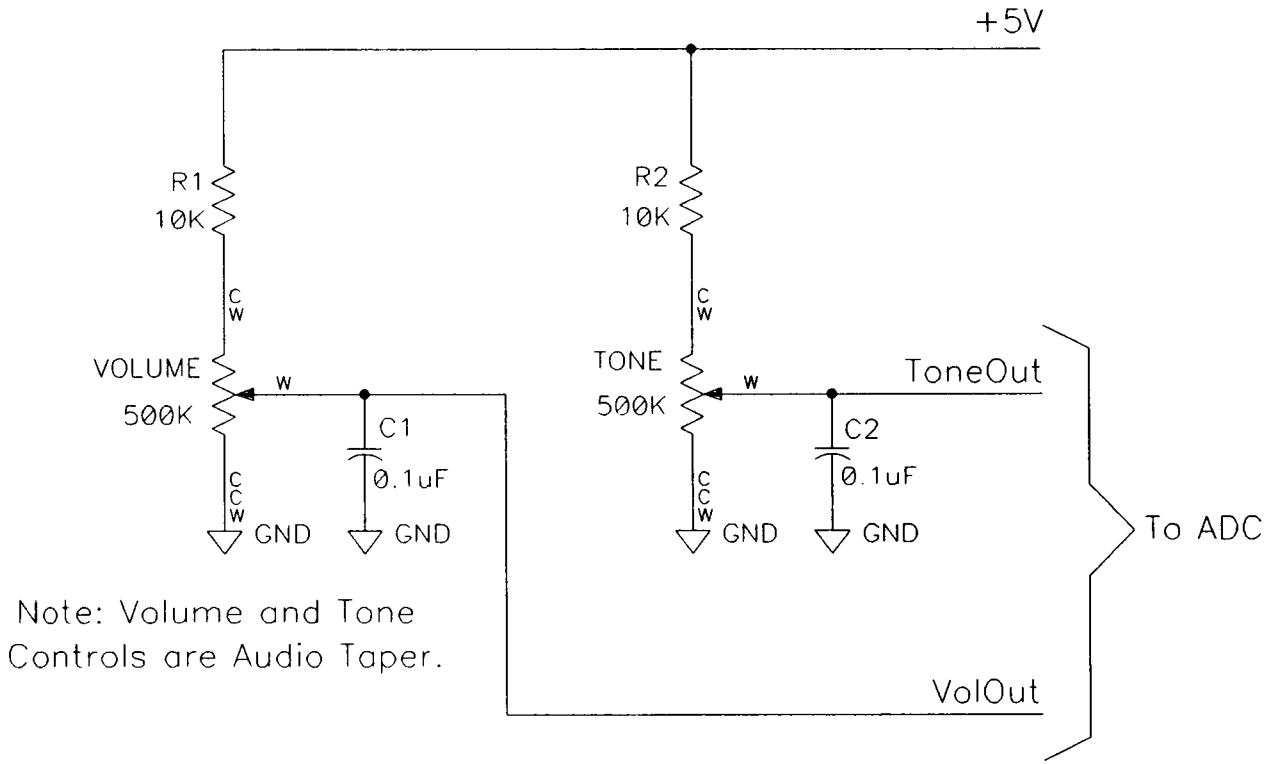



**Figure 4.6.2 User Controls, Volume and Tone Potentiometers.**

Finally, programming is controlled by a four-position rotary switch and a single pushbutton switch. Three of the rotary switch positions are memory locations. The 4th rotary switch position is the "live" position. Normally, the guitarist would leave the rotary switch in the live position. Once a desired volume, tone, and pickup combination is selected, the guitarist would depress the pushbutton switch. The program LED would then begin to flash. The rotary switch is then turned to the desired memory position. The program pushbutton is pressed a second time, this time causing the current guitar control status to be stored at the chosen memory location. Once the information has been logged by the microcontroller to memory, the program LED will cease to flash. The guitarist is then free to return to the live mode of operation or to use a previously stored configuration.

# 5. SYSTEM FIRMWARE

The analog circuits for the guitar controller were designed to be combined with a microprocessor. This would allow the user to not only control the guitar in real time, but to also store the guitar configuration in an on-board memory. Following is an outline of the program structure needed to implement the microprocessor control functions. This outline is not specific to any particular microprocessor or microcontroller.

## 5.1 Programming Outline

Figure 5.1.1 shows the guitar controller main program structure. The guitar control processor would, after power-up functions are complete, continually scan the guitar controls for user input. Upon receiving a user input, the processor would transfer this data to the Volume/Tone and switch matrix control inputs. LED's can be used to provide feedback to the user as to the current status of the processor. The design being outlined here assumes that the user has a choice of either live control operation or one of three memory locations.

During idle periods, some processors allow a sleep mode with reduced current demand. This sleep mode is usually interrupted through detection of bit changes at a specific port or interrupt line. This sleep mode would be entered after a predetermined time of inactivity at the processor inputs. Entering the sleep mode, in general, reduces the power demand for the processor by an order of magnitude.

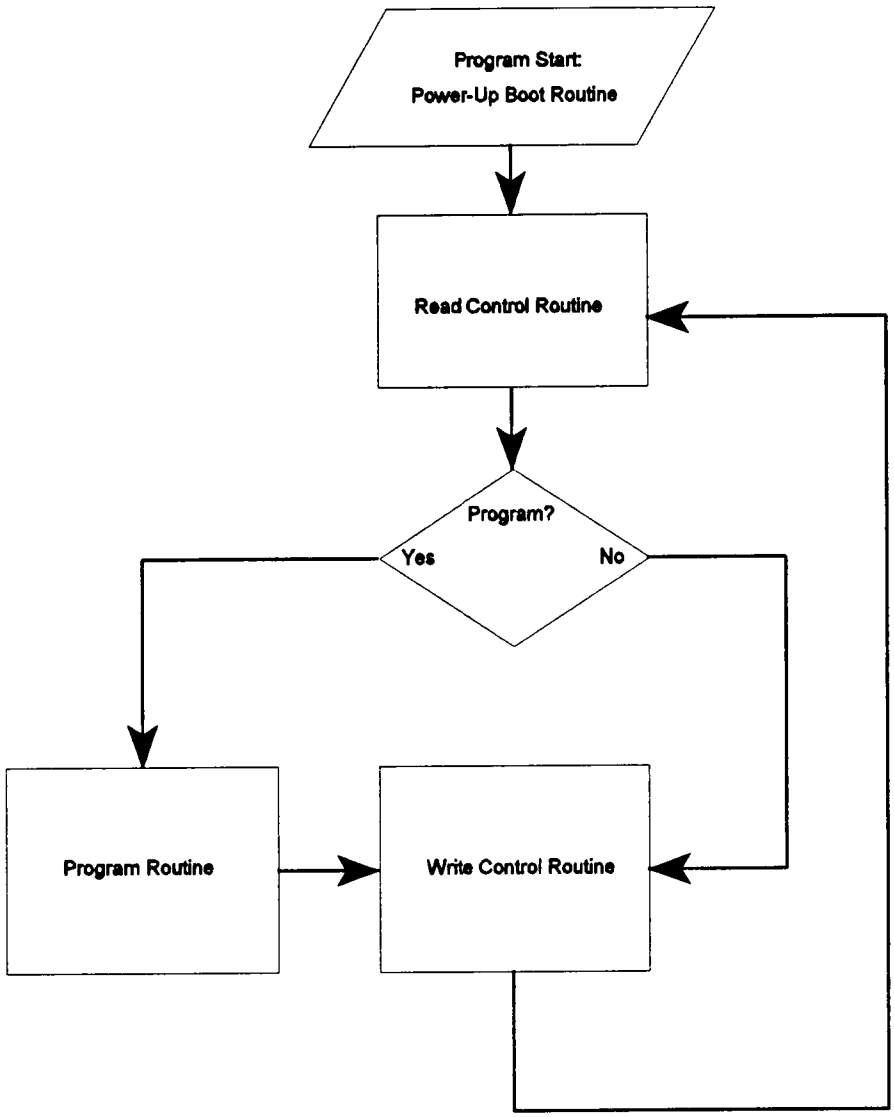



Figure 5.1.1 The Guitar Controller Main Program Structure.

In order to make the processor robust, it is wise to provide a watchdog timer function. Many microcontrollers on the market have a built in watchdog function. The watchdog will cause the power-up boot routine to be executed if a particular flag bit is not tended to by the software at regular intervals. Because of the relatively fast nature of most processors (timeout and reboot occur in a matter of a few milliseconds) the user would be unaware that a reboot had occurred (unless a memory setting was lost).

## 5.2 Program Block Descriptions

The firmware for the system microcontroller consists of four main program blocks. The first block is the Power-Up Boot routine. When power is first applied to the guitar controller, a number of housekeeping duties must be tended to. The watchdog timer must be initiated along with the status of the various I/O ports. As soon as these base functions have been completed the pickup state should be set such that no pickups are selected (mute condition). The DAC controls for the volume/tone circuit must be set to a default power up state (most programmable DACs will power up with all data set to zero). Next the processor must verify that all control inputs are valid. An invalid control status would be reported to the user by flashing of both the Program and the Low Battery indicator LEDs. With the ports configured and the DAC controls ready, and controls initialized, the boot routine is compete.

The second routine is the Read Control routine. This part of the firmware scans the user input control set and determines the data needed to program the volume/tone filter circuit DACs. Data from the controls would be stored in the program state register by this routine at each pass. The Read Control routine must determine whether the user has selected the program mode or is using the controls in live mode. The program mode select switch would be a latched input to the processor. The Read Control routine would also be the best place to tend to the watchdog timer control since this is the normal loop entry point for the control code during operation.

The third section of firmware is the Program routine. The Program routine is entered when the program mode pushbutton has been detected by the Read Control routine. This routine first clears the program mode switch latch and then checks the position of the rotary control switch. If the rotary control is not in the live position the program command is ignored and the routine ends. If the rotary switch is in the live mode, the routine activates the program LED in a flashing state. The routine then starts a program timeout timer and monitors the program pushbutton. Should the program timer reach its end of count without the pushbutton being actuated the routine would pass control to the next section of firmware. If the user depresses the pushbutton before the timeout, the Program routine would check the rotary switch to verify a valid memory has been selected (switch not in live mode). If the rotary switch is not in a valid memory position the program timeout timer is reset and the routine restarts. If the rotary switch is set to a valid memory location

then the current control settings are stored in the selected program memory. Once the memory is programmed the code execution continues at the Read Control routine.

The fourth, and final, section of firmware is the Write Control routine. This section of code reads a status word that indicates whether the live, memory 1, memory 2, or memory 3 data should be written to the guitar electronic controls. Once the appropriate data source is selected, the controls are programmed. It may be necessary to experiment with the programming order to prevent unwanted noise generation. After the controls are programmed, control is returned to the Read Control routine.

It might be possible to combine the Read Control routine with the power up boot routine. This would help to make the control system more robust, since a crash would simply cause the control program to branch back to the Read Control routine.

# 6. EXPERIMENTAL RESULTS

## 6.1 Magnetic Pickup Measurements

Since the strings on an electric guitar are not constrained to vibrate in a single mode or plane when a string is plucked, a very complex motion waveform exists on the string. Given the difficulty of exciting the string to produce exactly the same motion during experimental testing and the complex waveform present, it was found that some other method would be needed to verify the pickup response equation.

What was needed was a method of moving the string such that it's position versus time could be controlled. This would allow a velocity profile to be developed which can be used to derive the pickup response. Figure 6.1.1 shows the test configuration used. A direct current motor is used to drive a wooden shaft (dowel). A small (roughly 8 cm long) piece of guitar string is attached to the surface of this shaft. This section of string moves in a circular orbit above the pickup. The string position versus time can now be computed as shown in Figure 6.1.2. Here the distance between the string and the pickup magnetic pole piece is found using the law of cosines (Swokowski, 1979) as

$$x(\Theta) = \sqrt{2r^2(1-\cos\Theta)+2ra(1-\cos\Theta)+a^2} \qquad (6.1.1)$$

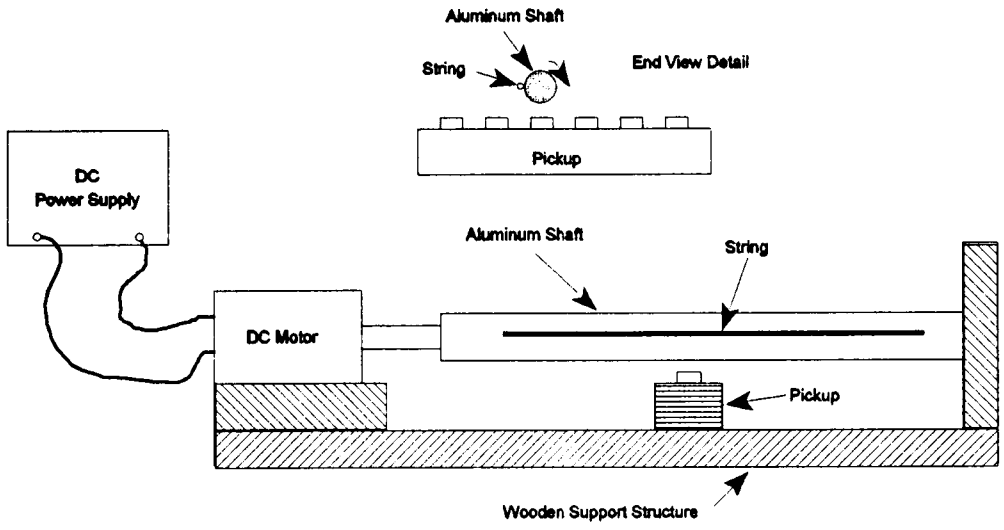



Figure 6.1.1 Magnetic Pickup Response Test Setup.

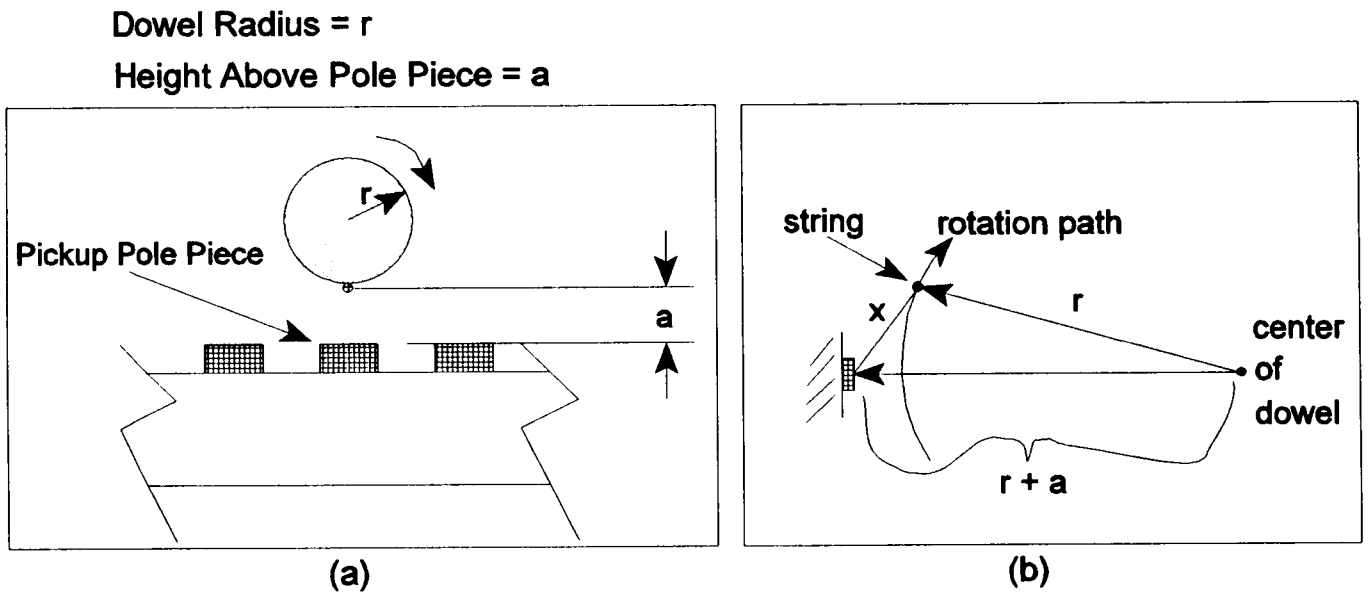



Figure 6.1.2 Rotating String Position Geometry.

Note that the top of the pickup pole piece is used as the position reference. It is anticipated that the pickup response as a function of string velocity is different for vertical and horizontal string motion. Ideally this test would constrain the string motion to one plane. By choosing a larger shaft size (and thus, larger orbit radius) one can approximate motion in one plane. If the shaft is made too large, then the string will pass over more than one magnetic pole distorting the response. Here a compromise is sought by choosing the shaft size to be smaller than the pole spacing but large enough to approximate planar motion.

To compute the string velocity, first Equation 6.1.1 is written as a function of time with $\Theta(t) = vt$, or

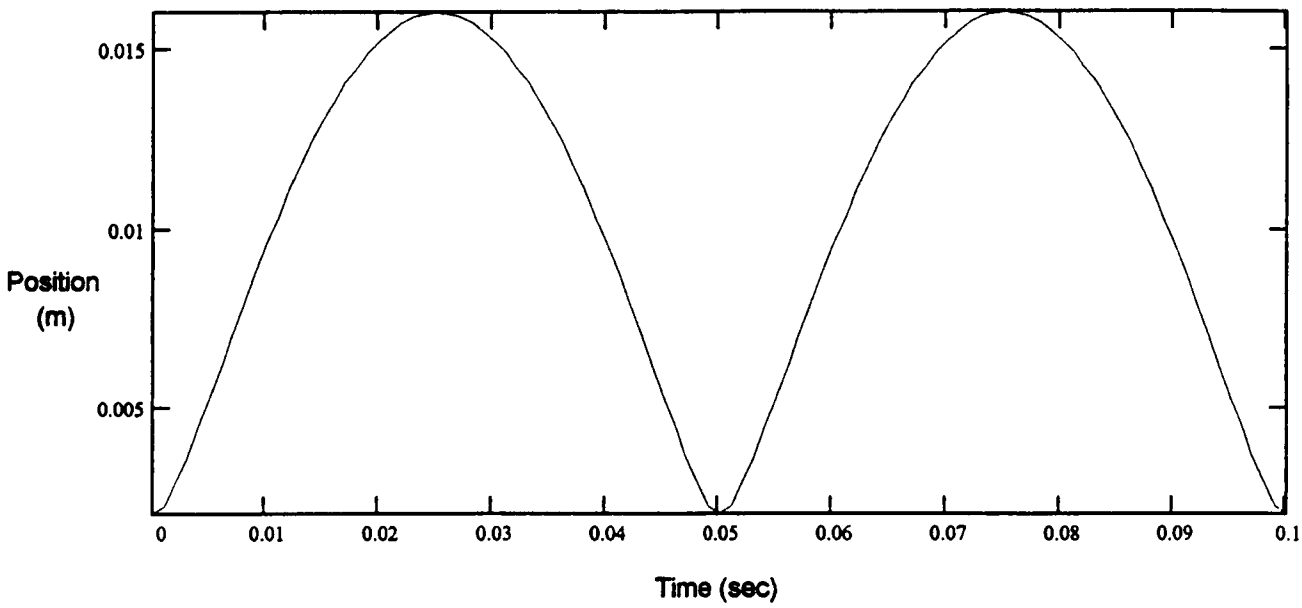
$$x(t) = \sqrt{2r^2(1 - \cos(vt)) + 2ra(1 - \cos(vt)) + a^2} \tag{6.1.2}$$

Then the string velocity v(t) is

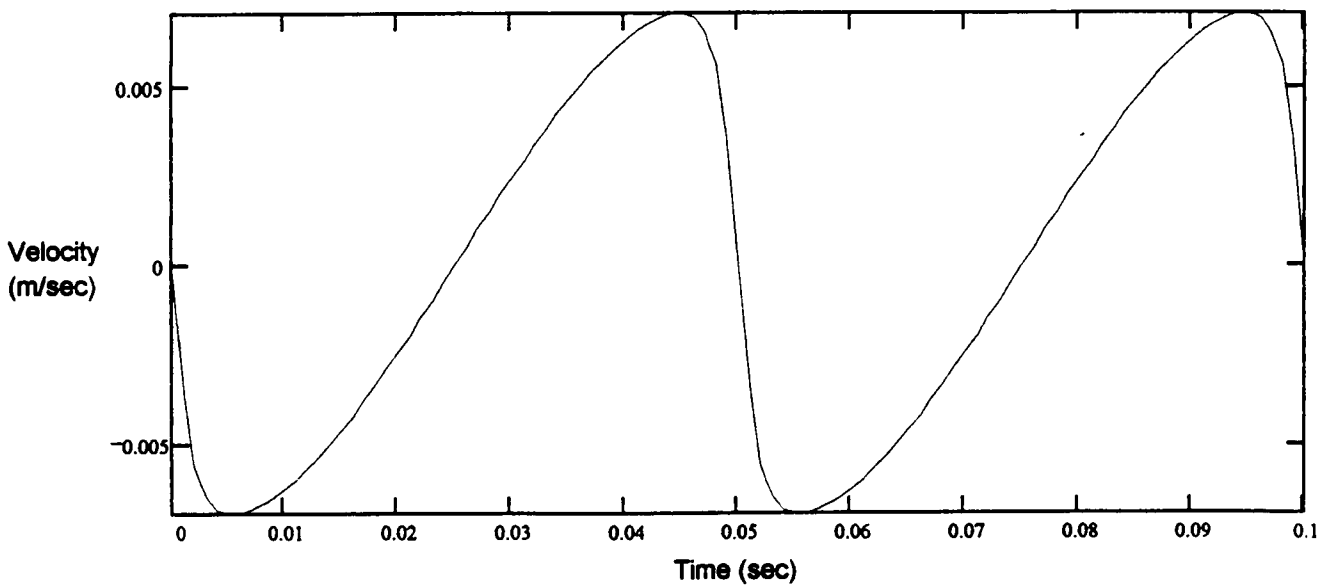
$$v(t) = x'(t) = \frac{r^2 \sin(vt) + ra \sin(vt)}{\sqrt{2r^2(1 - \cos(vt)) + 2ra(1 - \cos(vt)) + a^2}} \tag{6.1.3}$$

where v is the angular velocity of the shaft in radians per second. Equations 6.1.2 and 6.1.3 are illustrated in Figure 6.1.3. Note that the velocity is non-linear, looking nearly like a sawtooth waveform.

Figures 6.1.4, 6.1.5, and 6.1.6 show the oscillograph data for the pickup where three different rotation velocities were used. The output of the pickup was




(a)




(b)

Figure 6.1.3 String Position and Velocity for a Rotating Shaft.

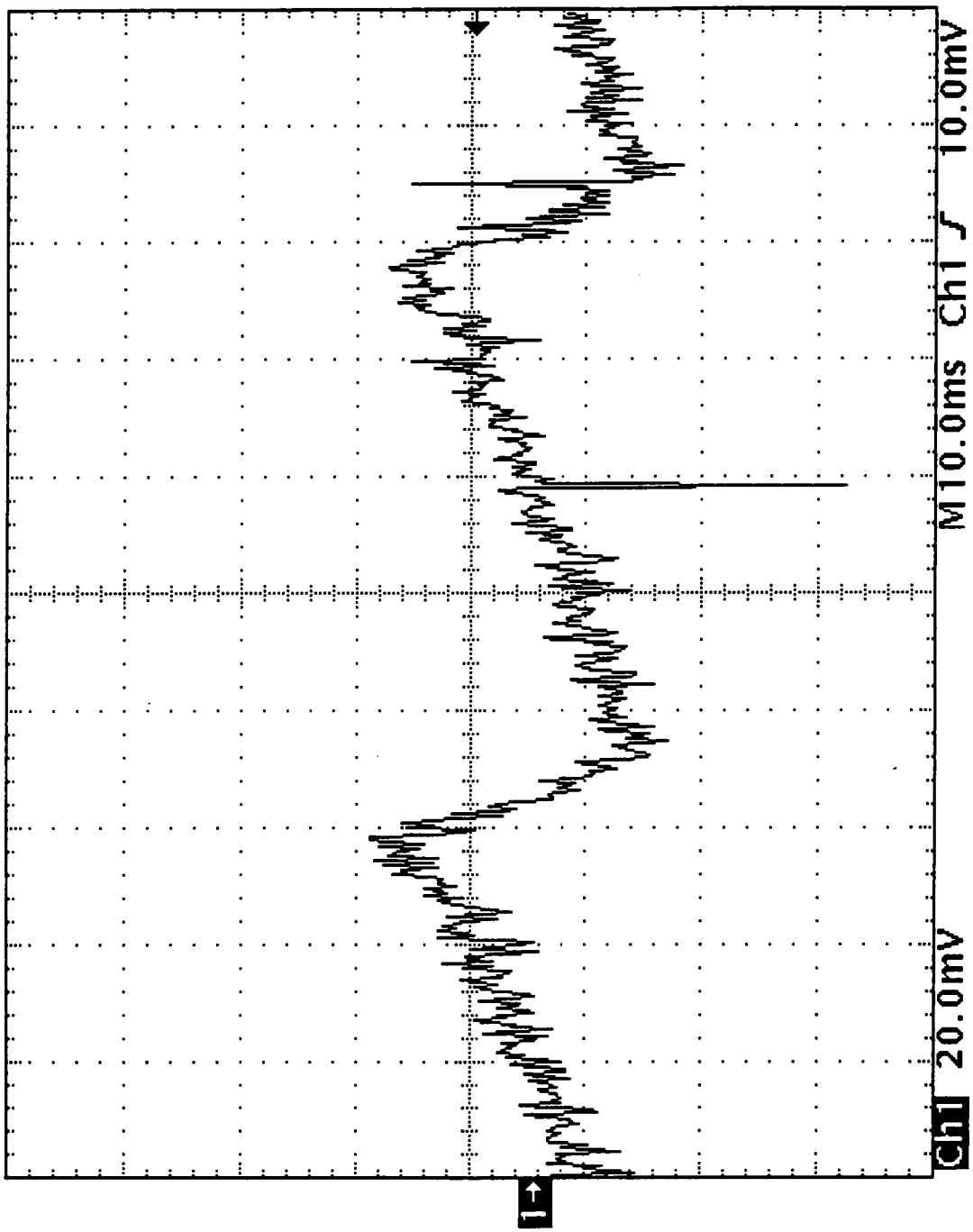



Figure 6.1.4 Pickup Response to String on a Rotating Shaft (1200 Rpm).

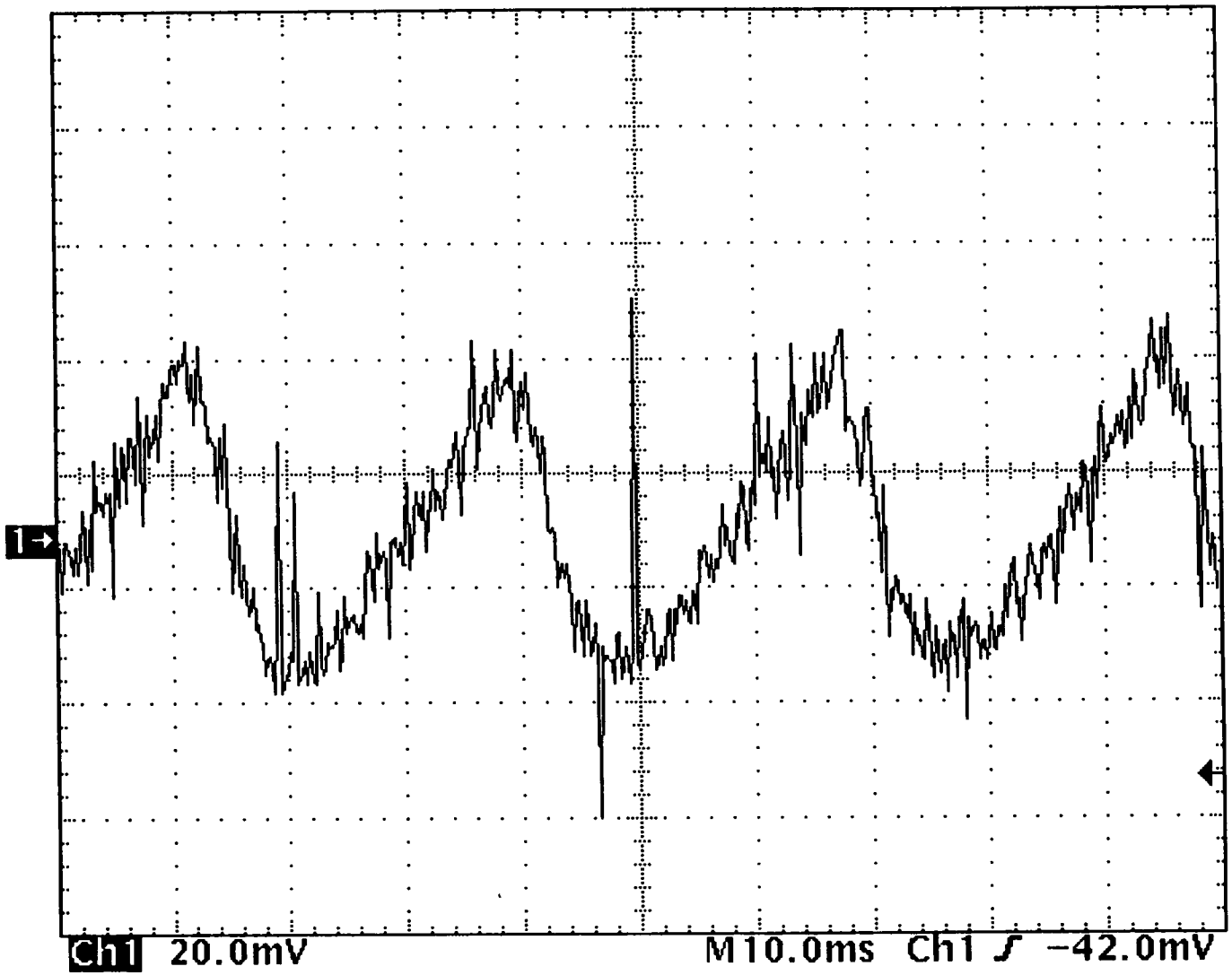



Figure 6.1.5 Pickup Response to String on a Rotating Shaft (2220 Rpm).

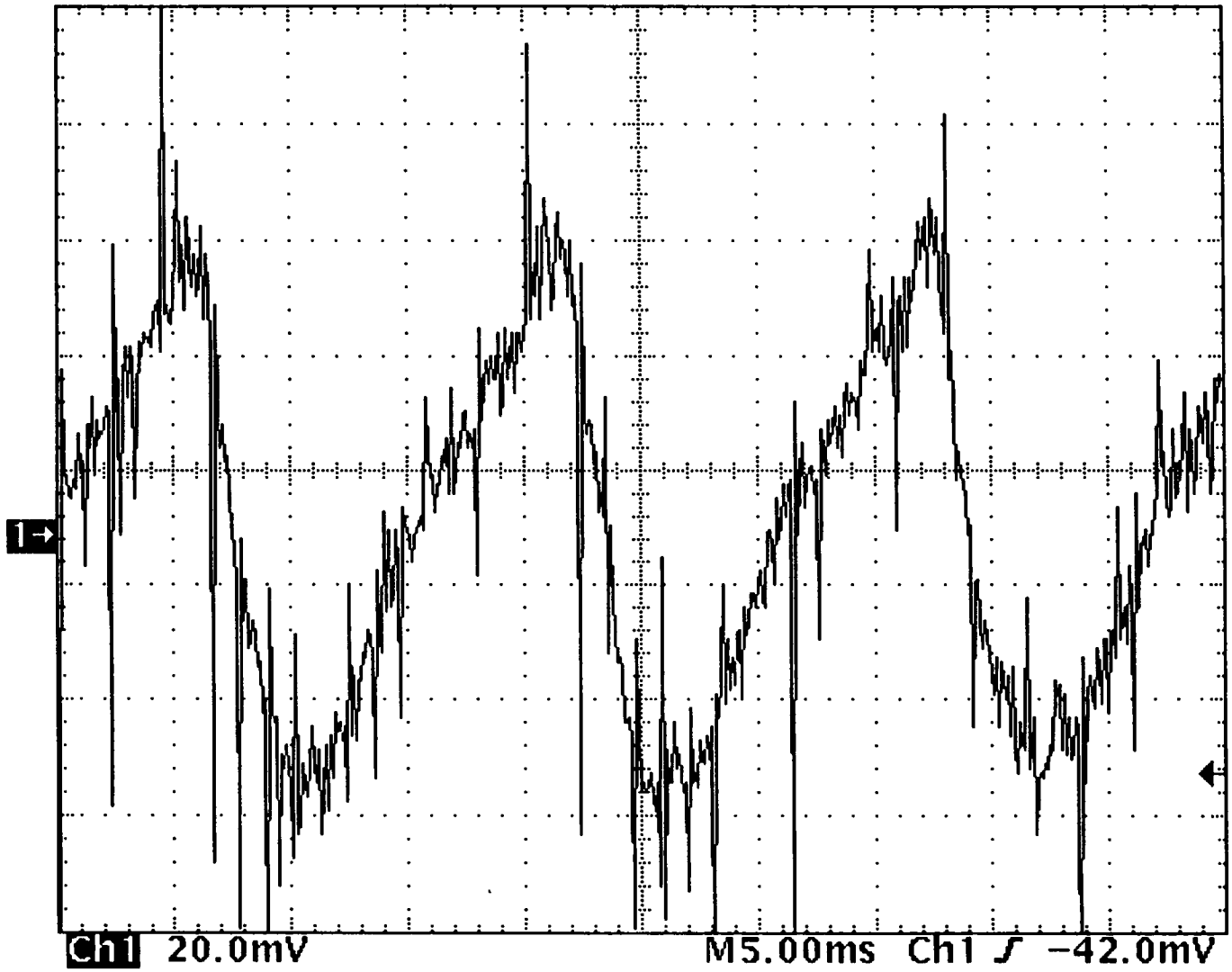



Figure 6.1.6 Pickup Response to String on a Rotating Shaft (3750 Rpm).

measured with a 1 megaohm, 1X scope probe. The oscillographs obtained closely followed the non-linear velocity profile predicted by Equation 6.1.3. Note that the voltage out of the pickup tracks the velocity for the two lower rotation speeds. Measurement error, difficulty in maintaining uniform spacing for the test string segment from the pickup pole piece, and the pickup frequency response account for lower than expected voltage seen at the highest rotation velocity. The non-linear portion of the traces may be due to differences in the pickup gain for vertical and horizontal velocity vectors. The low level noise present in these plots is due to acoustic vibration from the motor assembly and the high bandwidth of the oscilloscope used to make the plots. The intermittant spikes seen on the data are brush noise from the DC motor.

A test bed guitar was used with the pickup output directly available for analysis and the pickup position adjustable. Figure 6.1.7 shows the test bed guitar dimensions and layout. Figure 6.1.8 shows the pickup output for the conditions noted on the figure. Note that the presence of the fundamental oscillation frequency is nearly masked by the harmonic energy present on the string. Figures 6.1.9 and 6.1.10 show the frequency response plots obtained for two different pickup positions. For each of these plots the string was displaced a uniform distance (2 mm) at the same location along the string's length. The signals were averaged over roughly a 250 millisecond period. Note the presence of more high frequency energy for the pickup position nearest the bridge. Difficulty in exciting the string uniformly for the different test runs prevents direct comparison of the

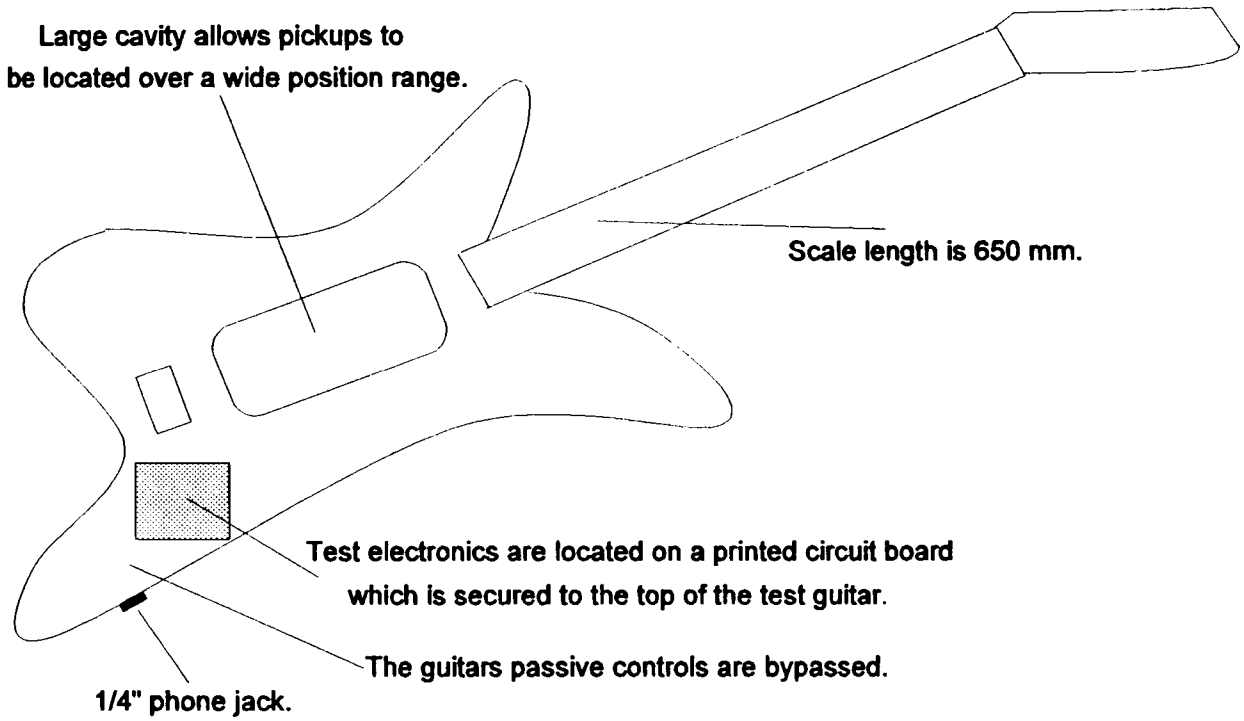



Figure 6.1.7 The Test-Bed Guitar Layout.

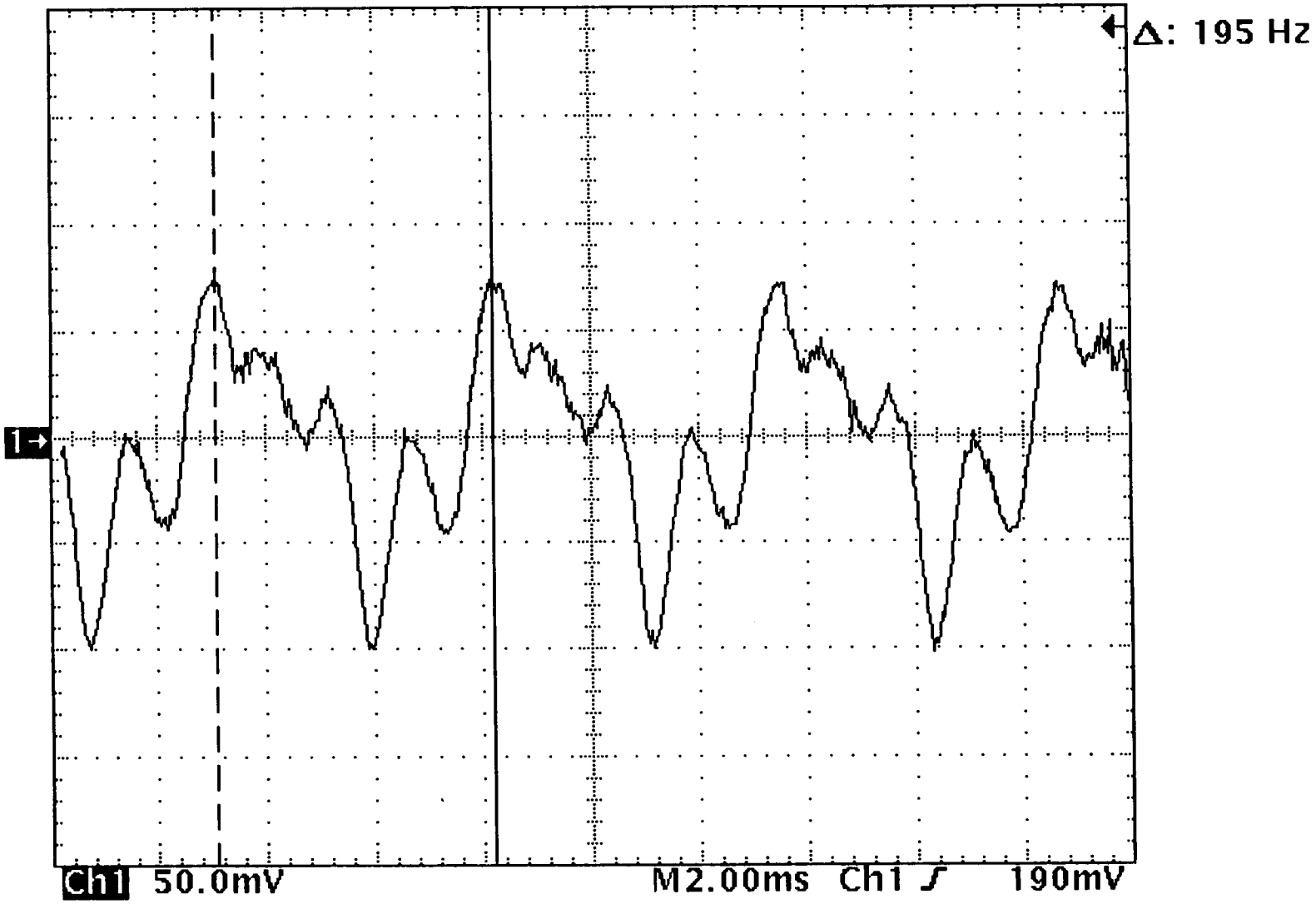



Figure 6.1.8 The Pickup Response, Pickup 4mm from String, String Plucked at the 12th Fret.

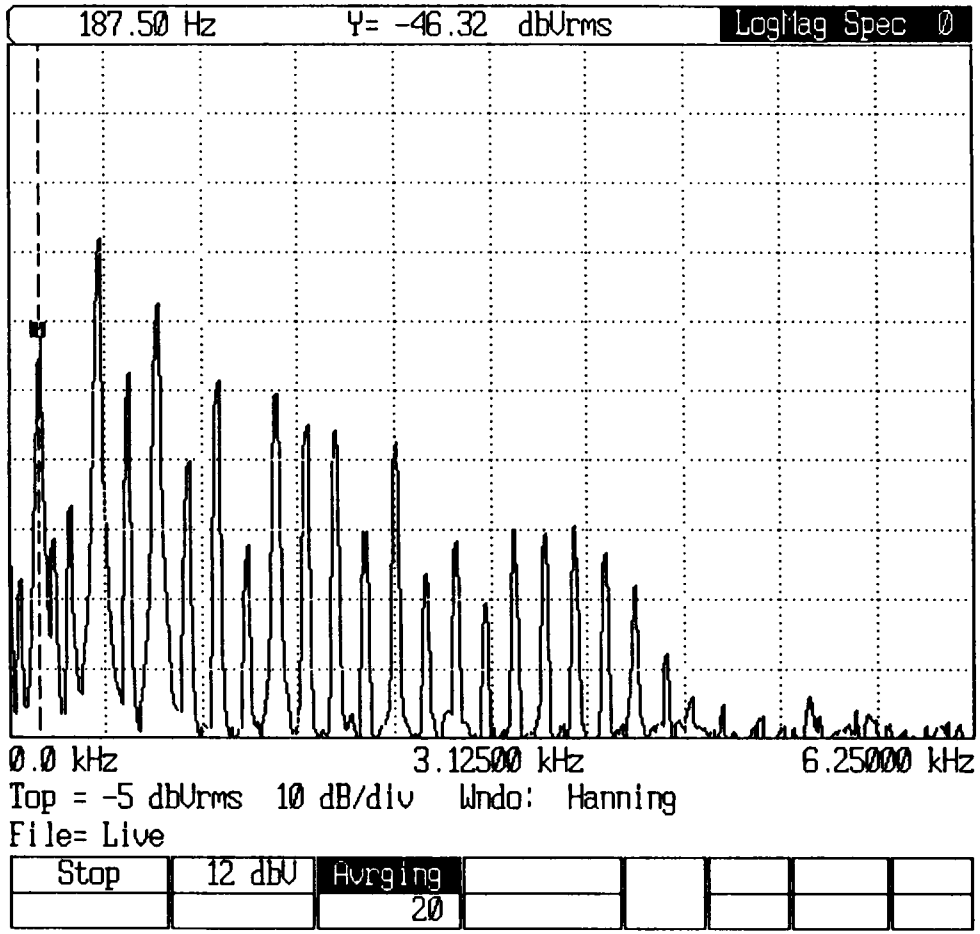



Figure 6.1.9 Pickup Output Spectrum for Pickup Located 8 cm from Bridge (Pickup 4 mm from String, String Plucked at 12th Fret).

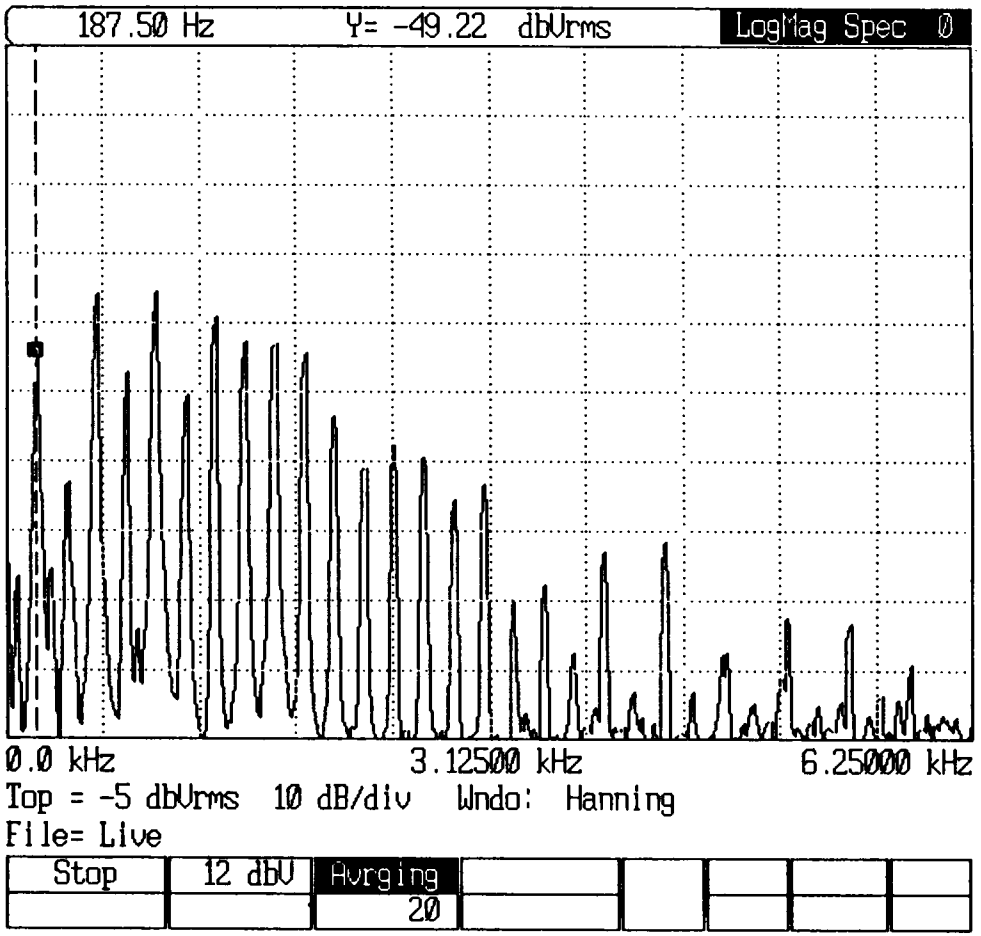



Figure 6.1.10 Pickup Output Spectrum for Pickup Located 3 cm from Bridge (Pickup 4 mm from String, String Plucked at 12th Fret).

response plots. Note that even comparing the relative amplitudes of each harmonic component to the fundamental can be deceptive, since the fundamental may change in amplitude at some pickup locations in relation to the other harmonics present.

One interesting playing technique used by guitarist is known as "chiming" the string. Here, the string is restrained (usually by lightly resting a finger on the string) at an appropriate location along the string's length. This creates a forced node at the finger position that restrains the string to be excited only in modes for which this is a node. Figure 6.1.11 shows the pickup response where the string was chimed at the 12th fret of the guitar (forcing a node at the half-length position on the string). Note that there is no energy at the fundemental frequency of the string since the string motion was constrained at the center of it's length. Chiming produces (as the name implies) a note that resembles a chime or bell. This must be due to the "purer" tone (fewer harmonics present) for a chimed string.

During testing of the guitar pickups it was noted how susceptible the pickups are to stray AC fields. A 1 megaohm scope input developed roughly a 40 mV signal when an AC powered drill motor was operated at a distance of over 3 feet from the pickup (note that the initial intent was to use the drill to drive the test shaft for pickup testing). With a DC motor a small amount of pickup occurred with a separation of several inches. The DC motor pickup was very high frequency in nature (most likely due to the motor brushes switching the motor's internal windings) and did not adversely affect testing of the pickup.

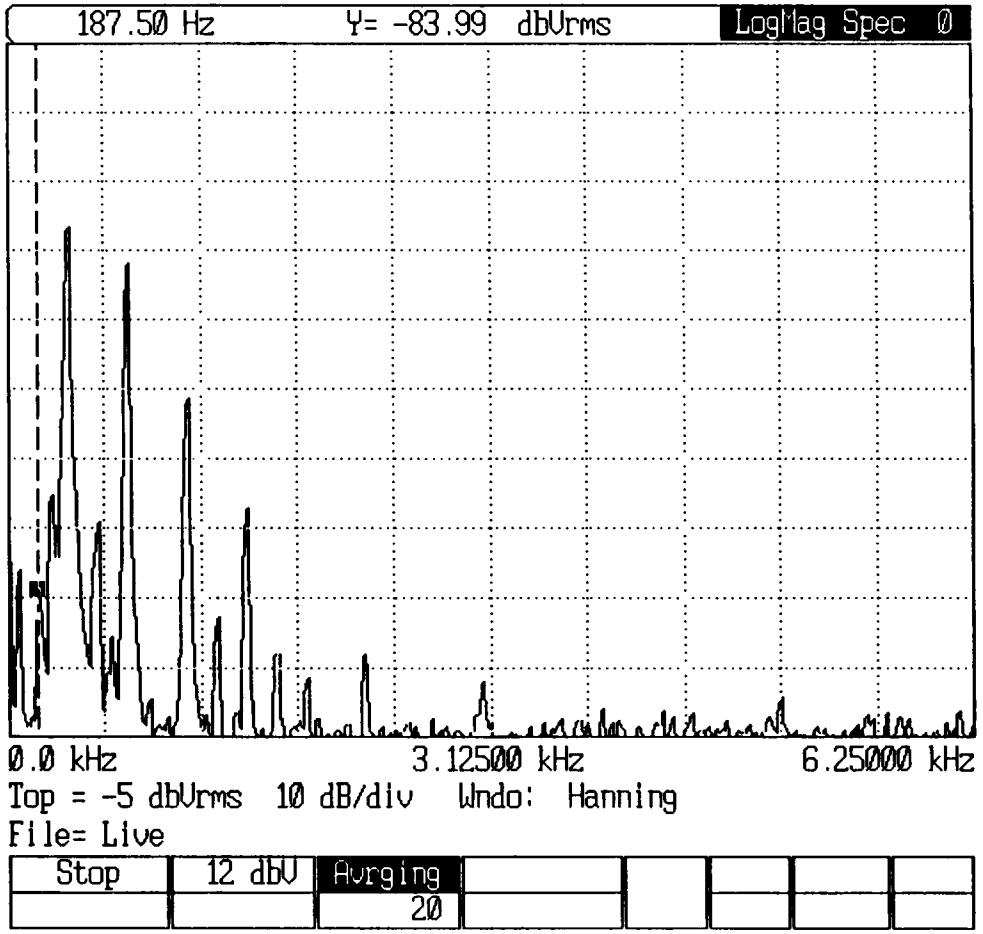



Figure 6.1.11 Pickup Output Spectrum for String Chimed at 12th Fret.

The pickups used for testing in this report were moderately susceptible to microphonic pickup. Lightly striking the pickup with a non-magnetic object could produce over a 100 mV signal into a 1 megaohm scope input. Note that the pickups used for testing were inexpensive, un-potted pickups from a budget guitar. Considerably less microphonic susceptibility would be expected from a more expensive, better built pickup.

The pickups used in the test bed guitar were analyzed to obtain the lumped model circuit values. The pickup inductance and resistance were measured using an LCR meter. The resonance peak was located using a swept tone coupled to the pickup by a wire coil of several turns. Data obtained from these measurements is summarized in Figure 6.1.12.

## 6.2 Battery Power System Test Results

The battery power system DC to DC converter was evaluated with a resistive dummy load. The input of the DC to DC converter was powered with a pair of AA batteries wired in series. The resistive load was sized to draw a current of roughly 20 mA. Measurements were made at the input and output with a clamp on current probe. The input voltage was measured as 1.95 volts. The input current waveform is a periodic set of pulses used to charge the converter output filter capacitor as needed. Figure 6.2.1 shows the input current and voltage waveforms. The oscilloscope's math function set was used to calculate the rms value of the input current, which was computed to be 74.9 mArms. The output current load was

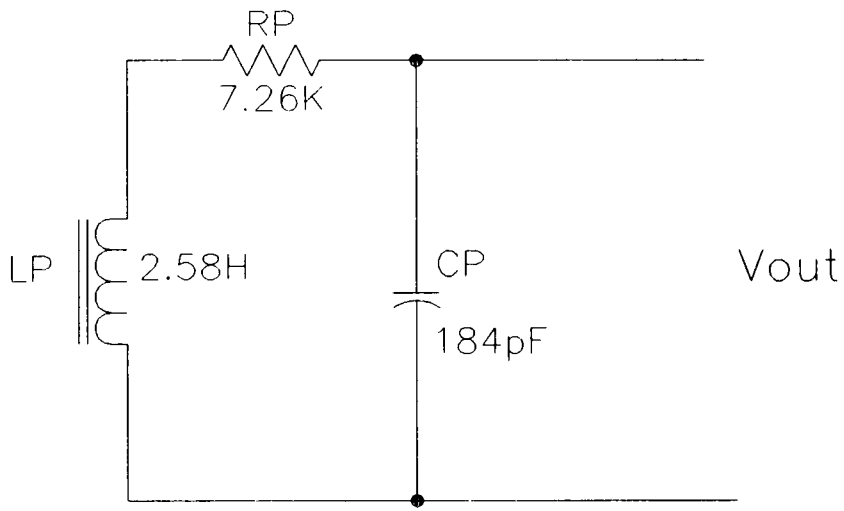



Figure 6.1.12 Test-Bed Guitar Magnetic Pickup Equivalent Circuit.

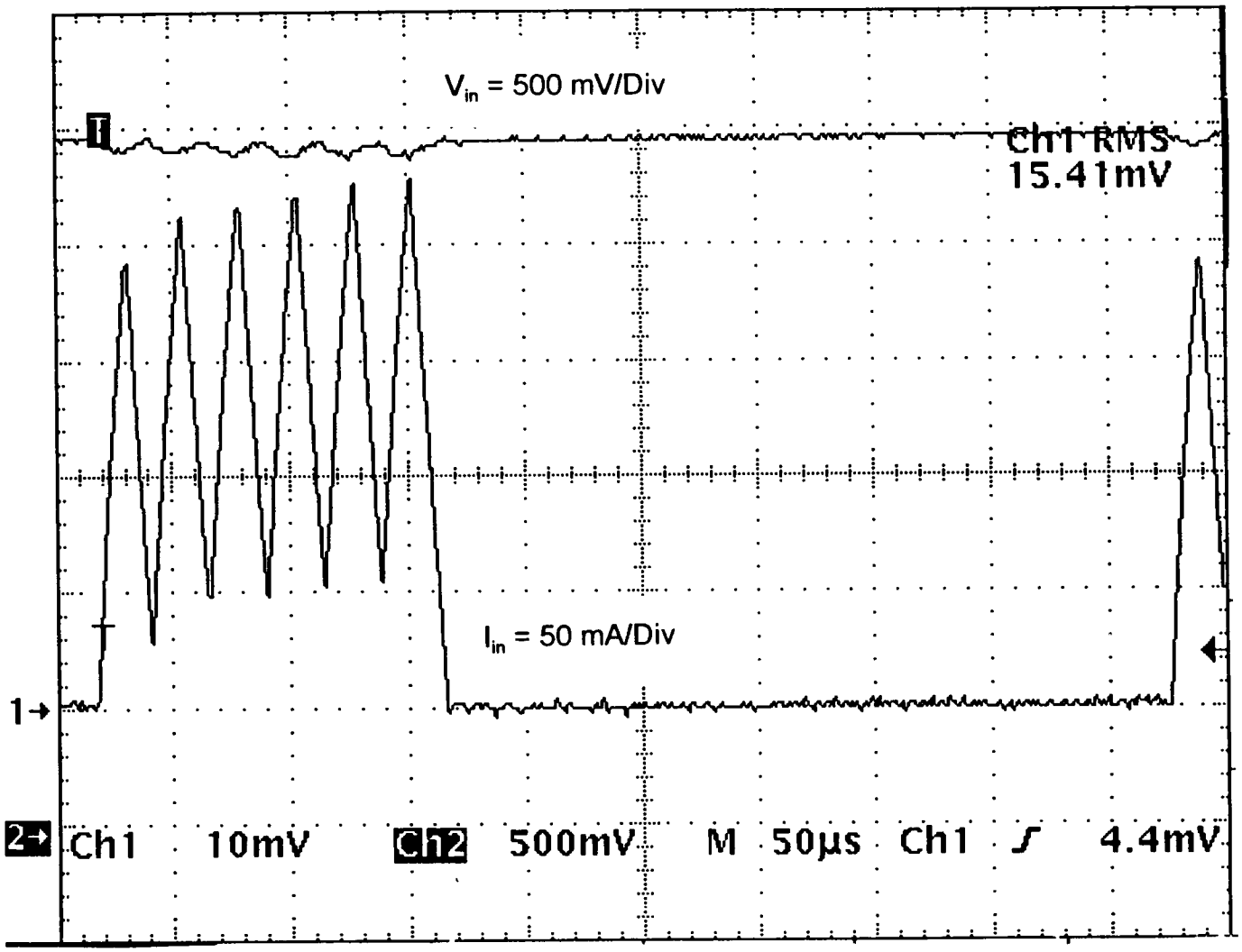



Figure 6.2.1 DC to DC Converter Input Current and Voltage versus Time.

measured to be 17.75 mA at a voltage of 5.0 volts. Plots of the output current and voltage are not included since these waveforms were found to be DC levels. Thus, the input power to the converter is 221 mWrms and the output power of converter is 88.7 mWrms. This gives a net power efficiency of 40.2%. This low value of efficiency is probably due to the poor efficiency of the inductor used in the test circuit. A high frequency ferrite core coil would probably bring the circuit efficiency up to the 70-80% range.

### 6.3 Pickup Switch Matrix Test Results

Operation of a prototype switch matrix was verified using the test-bed guitar as a signal source. The output of the switch matrix was used to drive the volume/tone control circuit during testing. An oscilloscope was used to verify the presence of signal at the appropriate nodes during operation.

### 6.4 Volume/Tone Control Test Results

The volume/tone control circuit was tested in three phases. These phases covered functional testing, an actual listening test, and lab evaluation of the frequency and transient response.

First, power was applied to the filter circuit (see Figure 4.5.3 in Section 4.5) with the feedback resistors from U1C and U1D to the input of U1A not installed. This allowed each stage of the filter to be checked for proper operation.

Second, all components were installed and the filter circuit was wired to the switch matrix. Two humbucking style pickups, temporarily mounted on the test-bed guitar, provided signals to the switch matrix circuit. The output of the volume/tone circuit was connected to a Fender guitar amplifier. At power up, three data codes must be programmed into the DAC in order to make the volume/tone circuit functional. DAC A was programmed to code 181 to set the Q for a Butterworth response. DAC C was set to code 25 for a gain of 1. Finally, DAC's B and D were loaded with the desired filter cut-off code. The circuit provided a very broad tone control range, from a "bright" open sound, to a lowpass cut-off that eliminated all but the lowest bass tones. One problem noticed was audible "pops" which occurred whenever one of the upper 3 bits of the filter code were programmed. Since data was loaded by hand on dip switches, it is difficult to tell if this was an artifact of the test set up or the circuit itself. It is possible that the dip switch data was unstable (switch bounce) as the switches were activated. This problem would have to be tested using a source of debounced 8-bit parallel data.

Third, and finally, the circuit was evaluated using a spectrum analyzer for frequency response and an oscilloscope for transient response. Since these plots were made as the transfer from the output of the switch matrix to the output of the volume/tone circuit, they cannot be directly compared to the plots found in Section 4.5. The frequency response plots (Figures 6.4.1, 6.4.2, and 6.4.3) were made using a chirp FFT technique, which accounts for the apparent noise at regular frequency intervals on the output spectra. The cut-off frequency for $D_f = 255$ was

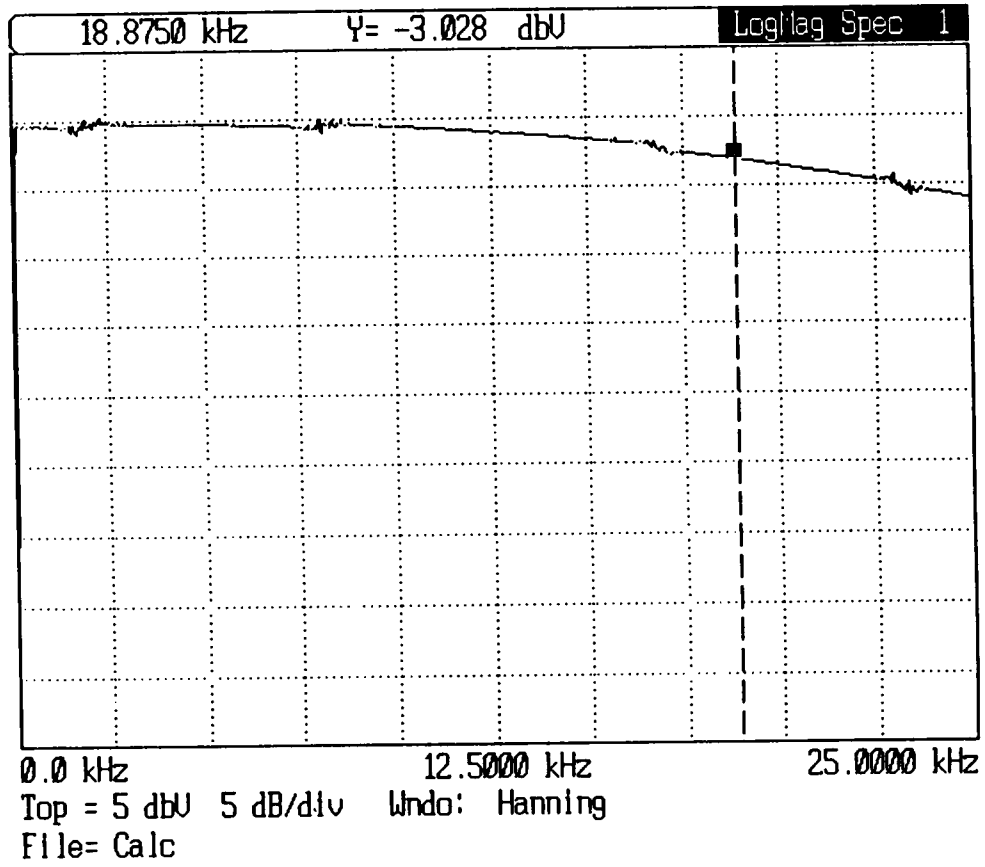



Figure 6.4.1 Volume/Tone Control Circuit Frequency Response, $D_f$ = 255.

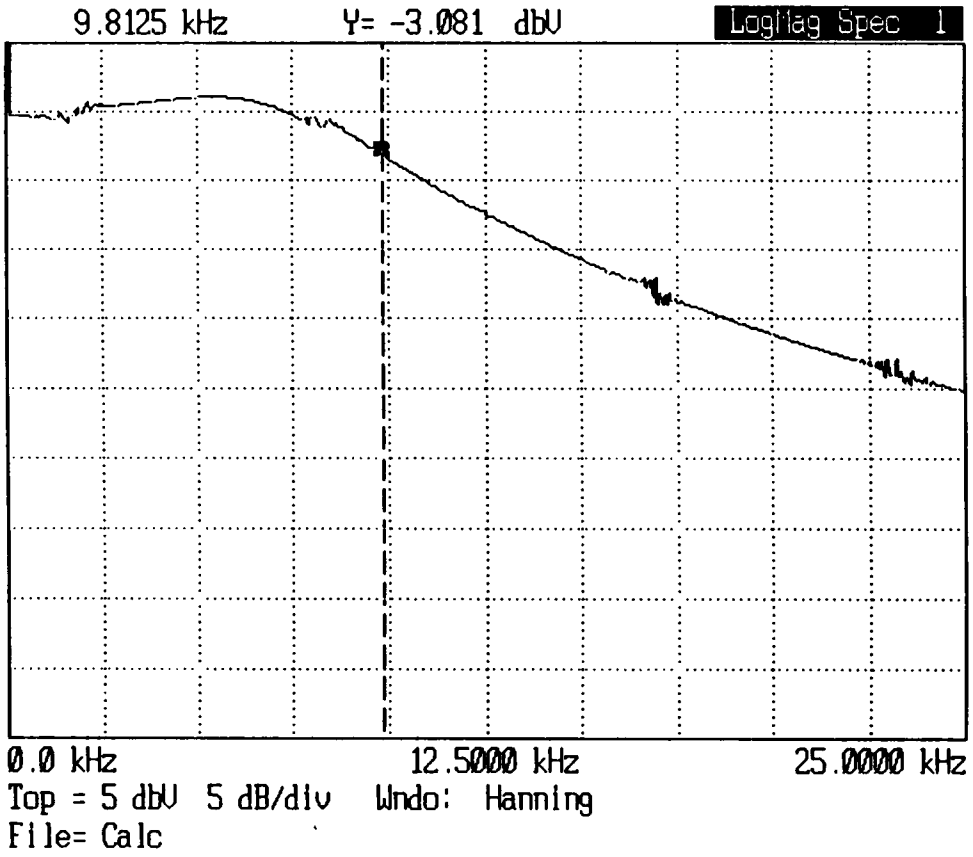



Figure 6.4.2 Volume/Tone Control Circuit Frequency Response, $D_f = 90$.

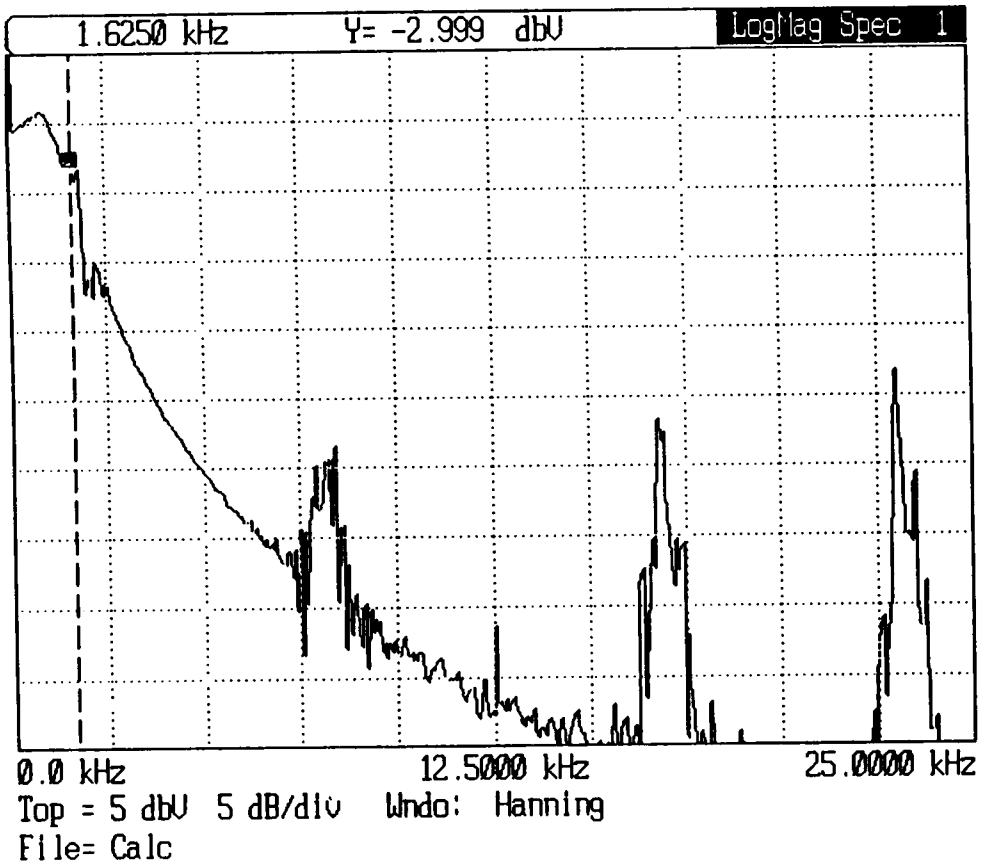



Figure 6.4.3 Volume/Tone Control Circuit Frequency Response, $D_f = 16$.

within 500 Hz of the calculated value (see Section 4.5). The transient response plots (see Figures 6.4.4, 6.4.5 and 6.4.6) agree with data values predicted by PSPICE with the settling time being negligible at $D_f = 255$ and several milliseconds for $D_f = 2$.

Note that, at $D_f = 2$, a large output voltage offset exists. This is due to the op-amp input offset current becoming significant as the DAC R-2R ladder divides the signal input current down. This can be avoided by limiting control range to the top 6 bits, leaving the lower two bits in a high state. AC coupling would also be useful to remove the output offset. Given the relatively low operating voltage, loss of dynamic range due to offsets could make the volume/tone circuit inoperable.

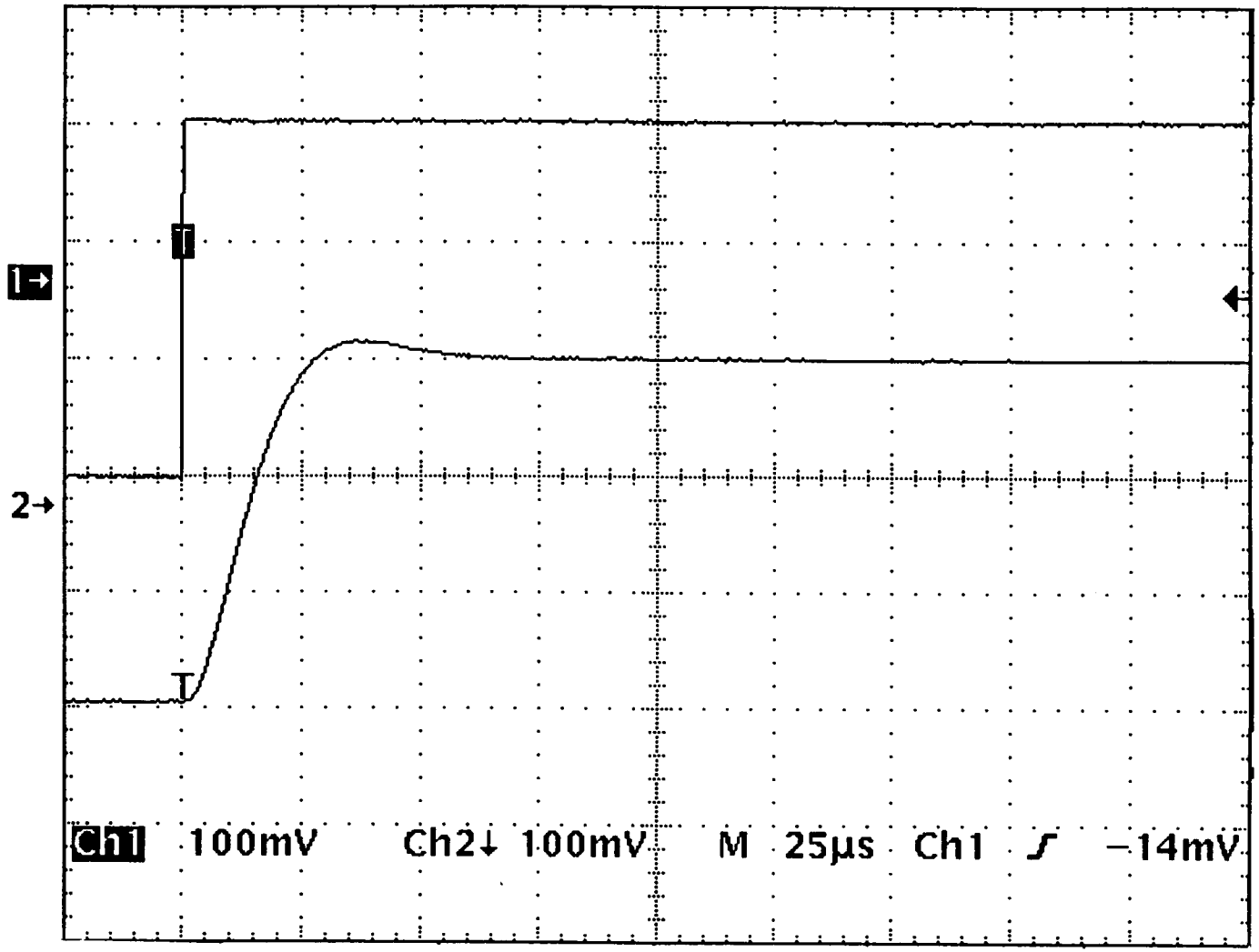



Figure 6.4.4 Volume/Tone Control Transient Response, 300 mV Step Input, $D_f$ = 255.

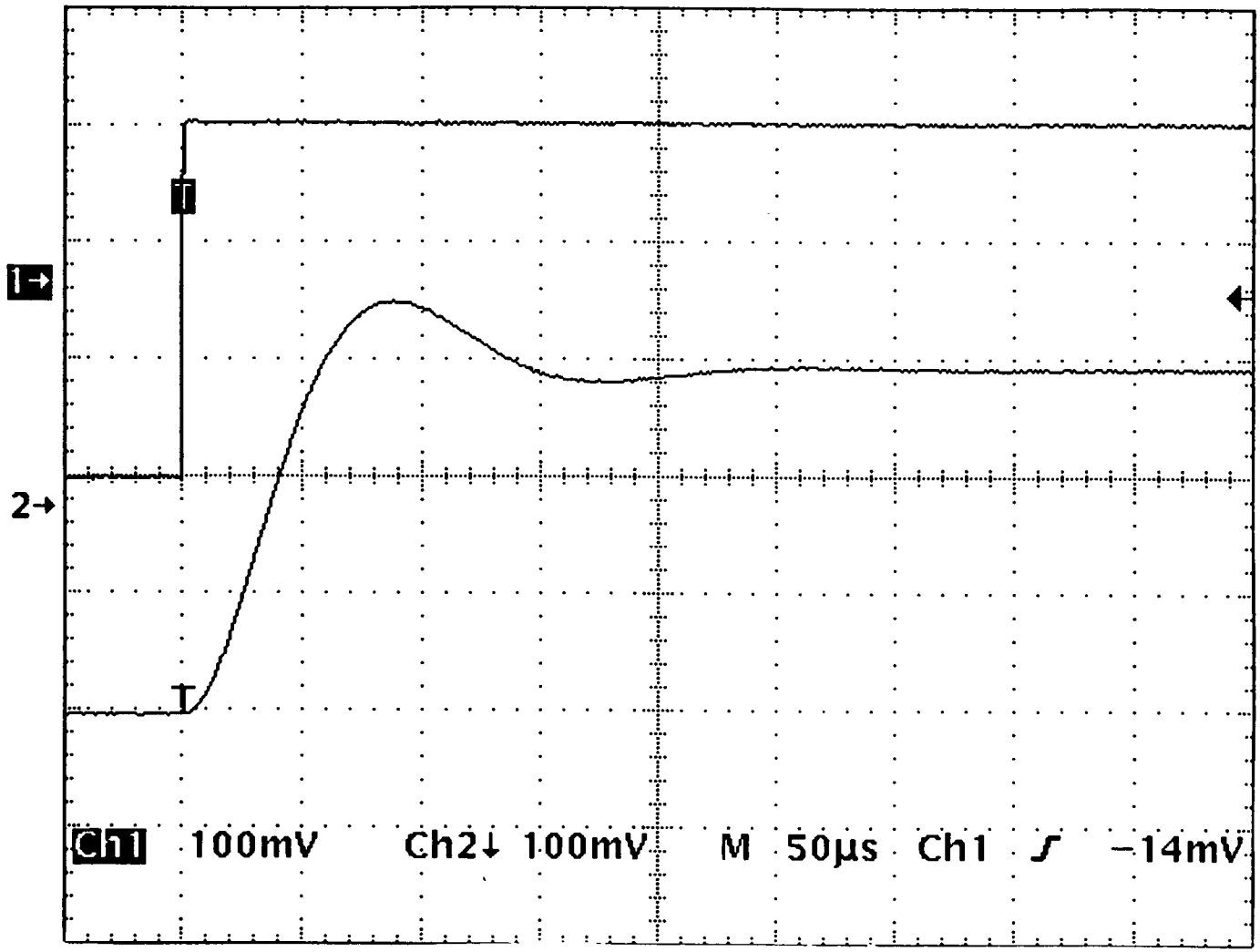



Figure 6.4.5 Volume/Tone Control Transient Response, 300 mV Step Input, $D_f$ = 90.

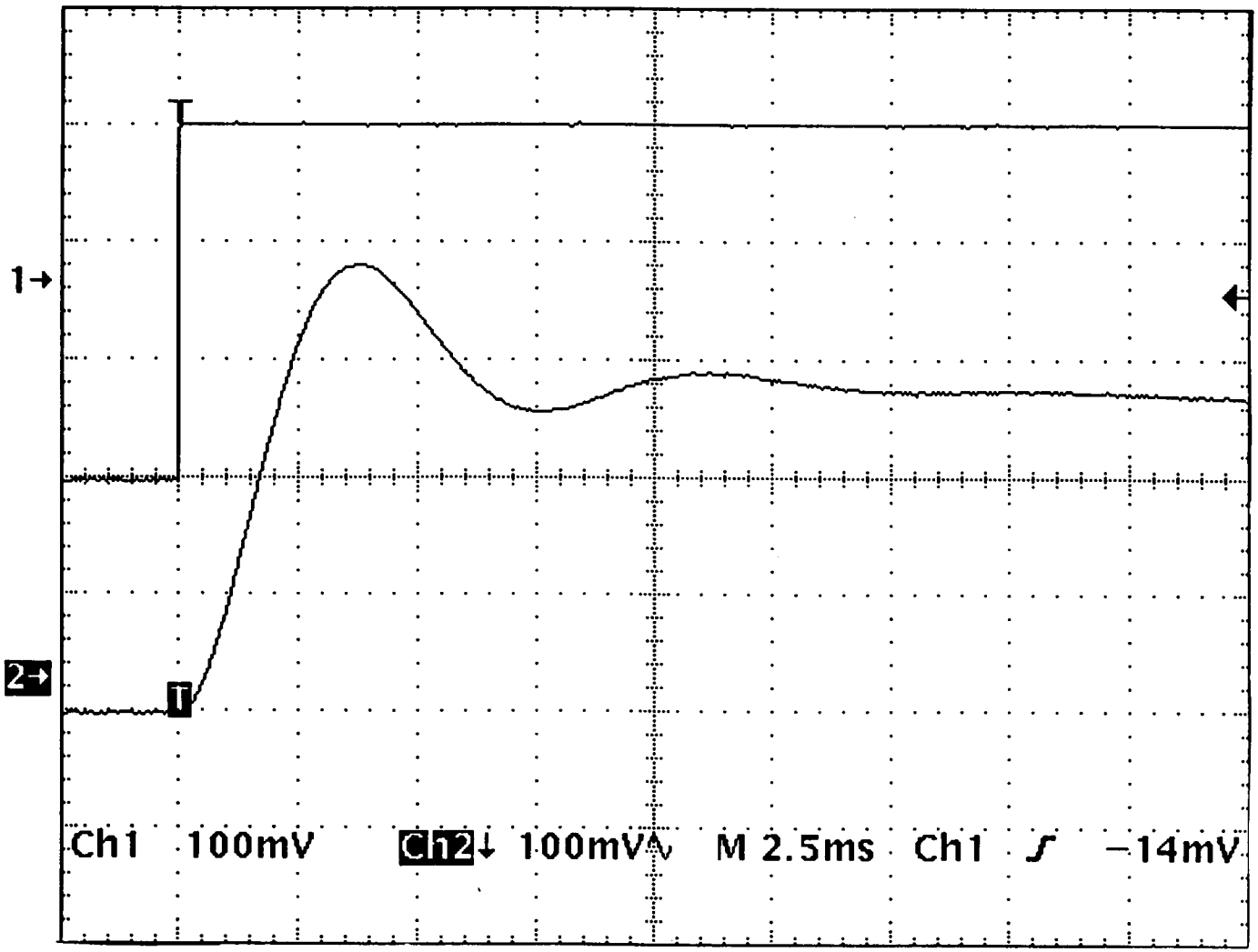



Figure 6.4.6 Volume/Tone Control Transient Response, 300 mV Step Input, $D_f = 2$.

# 7. CONCLUSIONS AND RECOMMENDATIONS

It has been shown that a successful battery powered electric guitar control system is feasible. The work done during this project has laid a foundation for a complete, operational, guitar control system. The use of DAC R-2R ladder circuits, to control the gain of an amplifier circuit or the time constant of an integrator, allowed the design of vary wide dynamic range control circuits. Achieving a 250:1 gain (or tuning) ratio in a filter circuit is quite impressive, given the relative simplicity of the circuit structure.

This work has provided insight into the complex relations of string motion and magnetics in the electric guitar. This should be of value to any guitarist wishing to better understand the electric guitar. The difficulty of predicting the performance of a pickup based on its position on the guitar remains, but at least a first order understanding of some of the physical interrelations has been achieved.

One issue that cannot be addressed using dip switches to program the filter control inputs (as was done in testing of the volume/tone circuit) is how appropriate the step sizes for volume and tone settings would be when a rotary input knob is used. It might be necessary to do some scaling of the control inputs to insure a that pleasing transition of volume and tone occurs during operation.

There are a number of issues that could be pursued in future work. The most obvious would be to complete a detailed design of the guitar control microprocessor with its associated firmware. Developing a remote, foot-operated

controller, that would allow memory access and foot pedal control of volume and tone would be a valuable addition to the design. This work could also explore wireless transmission of both the guitar signal and the control information for the guitar controller.

In the area of system physics, a more in depth evaluation of string motion, possibly applying stroboscopic photography techniques, might give more insight into how the string is effected by pluck location and pluck amplitude.

The ability of guitar magnetic pickups to directly sense the velocity of a moving string and produce a very substantial output voltage for very small motion distances suggests that other applications might exist for this type of transducer. Pickups with this sort of structure could be used wherever it is desired to monitor a changing magnetic field or the position of a ferromagnetic object.

Additionally, more work in the area of magnetic pickup design, specifically looking at how pickup structure effects the magnetic and electrical properties of the pickup would be of interest. Developing empirical relations amongst the many variables involved in the construction of a pickup assembly would be of value to pickup manufacturers.

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# APPENDIX

```
Guitar Pickup Circuit - no load
* J. W. Halliwell
* Thesis
* Figure 3.3.1 analysis

***** Circuit Definition
* pickup emf = Vs
* use 1 volt for AC analysis and 500 mS pulse for step analysis
Vs 1 0 AC 1 PULSE (0 1 100mS 1uS 1uS 500mS)

** Pickup Parameters used in Simulation
* inductance
LP 1 2 3H
* series resistance
RP 2 3 8K
* self capacitance
CP 3 0 200PF
* note that V(3) = Vout
***** end of circuit definition

***** Analysis
* ac analysis
.AC LIN 1000 10HZ 20KHZ

* transient analysis
.TRAN 1uS 500mS

* call probe
.PROBE
.END
```

```
Guitar Pickup Passive Tone Control
* John Halliwell
* Thesis
* Figure 3.3.5 analysis

***** Circuit Description
* pickup emf = Vs
* use 1 volt for AC analysis and 500mS pulse for step response analysis
VS 1 0 AC 1.0 PULSE (0 1 100mS 1uS 1uS 500mS)

** pickup parameters used in simulation
* inductance
LP 1 2 3H
* series resistance
RP 2 3 8K
* self capacitance
CP 3 0 200PF

* note that V(3) = Vout

* tone control
* capacitor
CT 3 4 0.02U
* potentiometer (use resistor model RTONE)
RT 4 0 RTONE 1

* volume potentiometer - no load at output of RV
RV 3 0 500K
***** end of circuit description

***** Analysis
* resistor model (to allow stepping of Rt)
.MODEL RTONE RES(R=1K)
* step RTONE 10K, 250K, 500K
.STEP RES RTONE(R) LIST 10K,250K,500K
* ac analysis
.AC DEC 20 10Hz 20KHz
* transient analysis
.TRAN 1uS 500mS
* call probe
.PROBE
.END
```

```
Guitar Electronic Control Filter Response
* John Halliwell
* Thesis 6/14/94
* Figure 4.5.3 analysis
* Based on ideal op-amp models with RIN=1000MEG and gain=100000

***** Circuit Description
** input source
* use 1 volt for AC analysis, 500mS pulse for transient
Vin 1 0 AC 1.0 PULSE (0 1 100mS 1us 1us 500mS)

** Pickup Parameters used in Simulation
* inductance
LP 1 2 3H
* series resistance
RP 2 3 8K
* self capacitance
CP 3 0 200PF
* note that V(3) = Pickup output

*** SV filter circuit
** input buffer circuit (U3)
* v controlled v source , gain= 1, RIN=1000MEG
RINBUF 3 0 1000MEG
EINBUF 4 0 3 0 1

** input gain circuit (U2A)
* v controlled - v source , gain= -100000, RIN=1000M
RAMP1 5 0 1000MEG
EAMP1 6 0 0 5 100000

** first integrator (U2B)
* v controlled - v source , gain= -100000, RIN=1000M
RINT1 7 0 1000MEG
EINT1 8 0 0 7 100000

** second integrator (U2C)
* v controlled - v source , gain= -100000, RIN=1000M
RINT2 9 0 1000MEG
EINT3 12 0 0 9 100000

** Q amp (U2D)
* v controlled - v source , gain= -100000, RIN=1000M
```

```
RQAMP 10 0 1000MEG
EQAMP 11 0 0 10 100000

** control resistors
* R1 and R2 set the filter cut-off
R1 6 7 RTONE 1
R2 8 9 RTONE 1
* R3 and R4 set the Q = R3/R4 = 0.7071
R3 11 10 70.71K
R4 8 10 100K
* feedback
R5 12 5 100K
* input amp
R6 6 5 100K
* gain adjusting resistor RGAIN, set for gain=1
R7 4 5 100K
* Q amp gain
R8 11 5 100K

** integrator caps
* first integrator
*RC1 7 8 10K
C1 7 8 820pF
* second integrator
*RC2 9 12 10K
C2 9 12 820pF
** resistor models
.MODEL RTONE RES (R=1)
*.MODEL RGAIN RES (R=100K)
** step value of filter cut-off resistor
* RTONE=1280K  >  data = 2
* RTONE=28.44K    >  data = 90
* RTONE=10.04K  >  data = 255
.STEP RES RTONE(R) LIST 1280K,28.44K,10.04K
**** end of circuit description
* ac analysis
.AC DEC 20 10Hz 20kHz
* transient analysis
.TRAN 1uS 500mS
* call probe
.PROBE
.END
```

# VITA

John William Halliwell was born on March 27, 1962, in Madrid, Spain. Son of a career Air Force fighter pilot, Mr. Halliwell lived throughout the southeastern US. In 1975 his family settled in Hampton, Tennessee where John graduated from Hampton High School in 1980. After graduating from high school he attended the University of Tennessee (UT) in Knoxville, Tennessee. He graduated from UT in 1985 with a Bachelor of Science degree in Electrical Engineering, where his studies emphasized analog instrument design.

After receiving his bachelor's degree, Mr. Halliwell went to work for EG&G Energy Measurements in Las Vegas, Nevada. There he was responsible for the design of test and calibration instruments for high speed data acquisition systems.

In 1987 he joined the Fusion Energy Division of the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. There he was responsible for design, testing and installation of various data acquisition and control system electronics for the Advanced Toroidal Facility fusion reactor. In 1989 he transferred to the Instrumentation and Controls Division of ORNL, where he continues to work in electronic systems design and testing with an emphasis on analog instrument design.