

Chapter 2

Pickups, Volume, and Tone Controls

Introduction

A pickup is an example of what an engineer would call a *transducer*. A transducer is a device that transforms a non-electrical quantity (temperature, strain, pressure, velocity, etc.) into an electrical signal. Of course, here we are interested in converting the vibration of a string into a corresponding electrical signal.

Volume controls are variable attenuators used to vary the amplitude of the signal produced by a guitar. Tone controls are adjustable filters that modify the frequency response of the instrument pickups. This chapter covers the basic theory of pickups, volume controls, and tone controls, and their interaction.

Single-Coil Magnetic Pickups

If a conductor moves through a magnetic field, a voltage will be induced in that conductor. This is shown in Fig. 2.1. Assuming a uniform field, the amplitude of the voltage is proportional to the speed at which the wire cuts through the lines of flux and the number of turns of wire. The equation for the induced voltage is called Lenz's law, which is

$$V = N \frac{d\Phi}{dt} \tag{2.1}$$

where $d\Phi/dt$ is the rate of change of magnetic flux, which is directly proportional to the speed at which the wire cuts through the lines of flux, and N is the number of turns of wire.

If we were to move the wire back the opposite direction through the field, the polarity of the induced voltage would be reversed. Flipping the magnet over so that

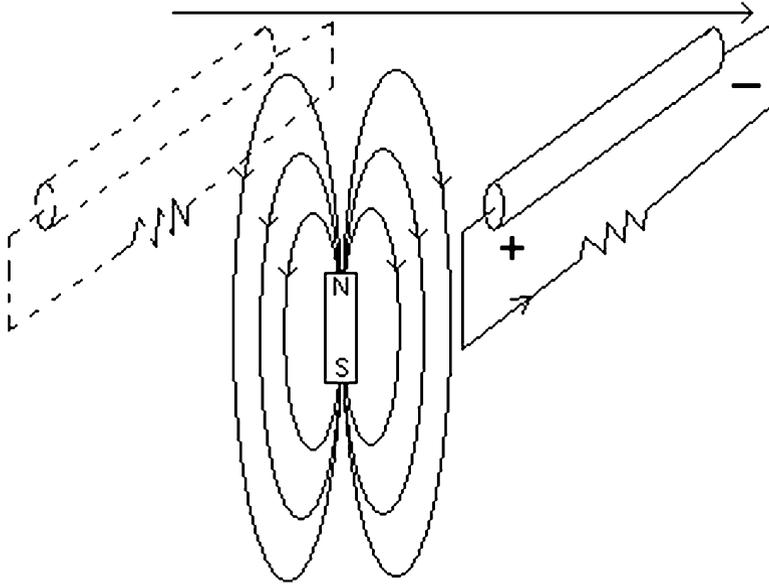


Fig. 2.1 Relative movement of a conductor and magnetic field induces a voltage in the conductor

the south pole is facing up will also reverse the polarity of the induced voltage, relative to the direction of motion.

Imagine that the wire in Fig. 2.1 is a steel guitar string that was plucked and is vibrating back and forth over the pole of the magnet. A time-varying, AC voltage would be induced in the string, and in principle we could use the signal induced in the string itself as the output.

In an actual magnetic pickup, many (usually several thousand) turns of wire are wrapped around a magnet with cylindrical pole pieces located below each guitar string. The pole pieces couple the magnetic field to the strings. Because the string is made of steel, as it vibrates and moves back and forth over the pole, the magnetic field is distorted. This movement of the field induces a voltage in the coil, which serves as the guitar signal. In the typical single-coil magnetic pickup there is one magnetic pole piece for each string and the coil is wound around all magnets as shown in Fig. 2.2.

Waveforms produced using a Fender Stratocaster with standard single-coil pickups are shown in Fig. 2.3. The upper scope trace shows the waveform for the open A string, using the pickup closest to the neck of the guitar, with volume and tone controls set for maximum (full clockwise). There are three major signal characteristics that we are interested in here: amplitude, fundamental frequency, and overall waveform appearance.

As indicated on the scope readout, the amplitude of the waveform is about 198 mV_{P-P}. Signal amplitude varies tremendously with the force used to pick or strum the strings and with pickup height. The time I took between hitting the note

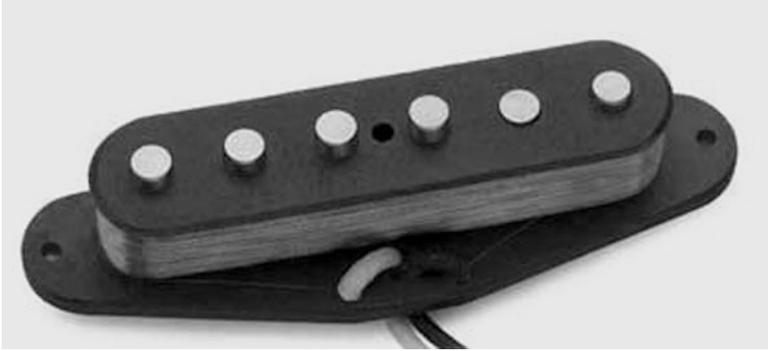


Fig. 2.2 Typical single-coil magnetic pickup

and capturing the scope display also greatly affected the amplitude of the signal, which decayed rather quickly from an initial spike in amplitude. Based on experimental measurements, this particular guitar produces a peak signal voltage somewhat greater than $400 \text{ mV}_{\text{P-P}}$.

Notice that the signal is complex, consisting of the superposition of many different frequency components. The fundamental frequency (or pitch if you prefer) of the A string should be 110 Hz. The oscilloscope is accurately indicating a fundamental frequency of 107.3 Hz, which is very close to the desired tuning.

Digital oscilloscopes often have trouble interpreting complex waveforms, such as those produced by speech musical instruments. If you are getting crazy frequency readings from your scope, you can perform a sanity check on the values by measuring the period of the signal in the old fashioned way, i.e., by measuring the time interval between peaks of the signal. Doing this with Fig. 2.3a gives period and fundamental frequency values of

$$\begin{aligned}
 T &= 4.6 \text{ div} \times 2 \text{ ms/div} & f &= 1/T \\
 &= 9.2 \text{ ms} & &= 1/9.2 \text{ ms} \\
 & & &= 109 \text{ Hz}
 \end{aligned}$$

The digital oscilloscope derives period and frequency information from the time between triggering events, which means that the scope is probably giving a more accurate reading than my visual estimate in this case.

It is interesting to compare the waveforms produced by plucking a single string vs. strumming a chord. Using the same guitar and pickup settings as before, the output signal produced by strumming the barre chord A (110 Hz fundamental) we get the waveform of Fig. 2.3b. The amplitude is somewhat greater than for the single string, and the waveform is more complex, consisting of additional harmonically related frequency components.

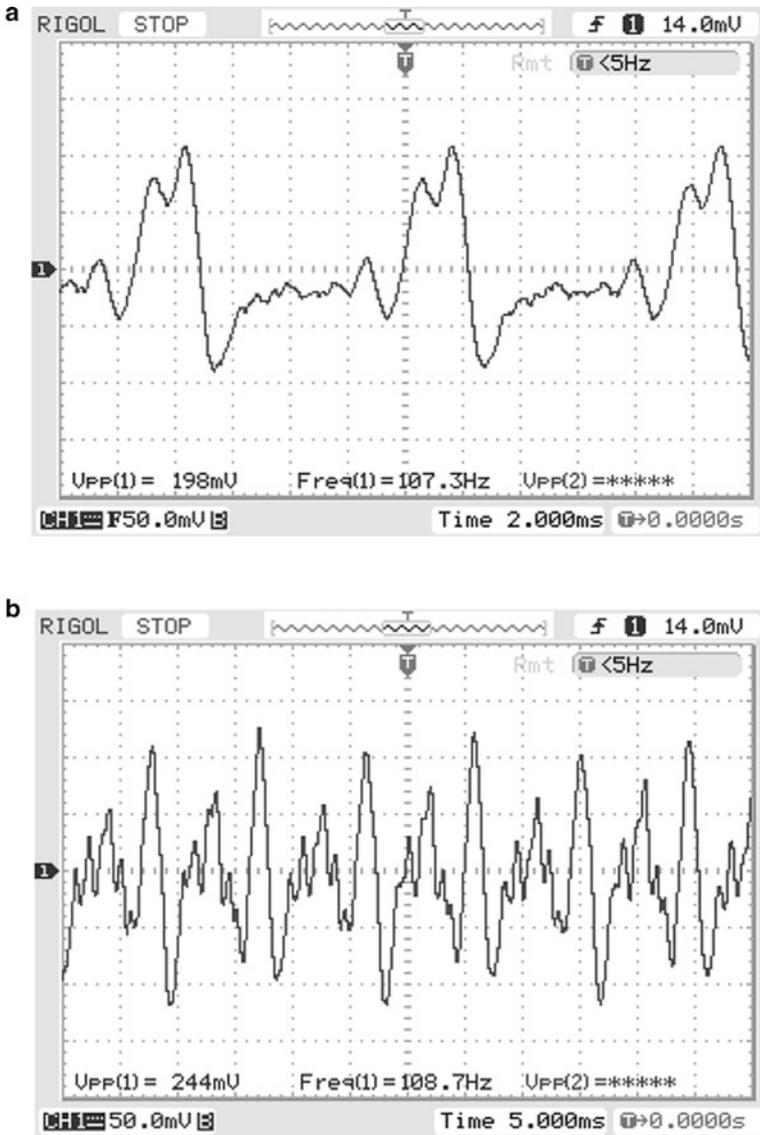


Fig. 2.3 Single-coil pickup waveforms. (a) Open A 110 Hz. (b) Barre chord A

Humbucker Pickups

Any conductor that carries current will produce a magnetic field. Wiring in the home may radiate enough 60 Hz energy that a significant voltage may be induced in a magnetic guitar pickup. This is a common source of annoying 60 Hz hum. Single-coil pickups are especially sensitive to this interference, where the pickup is acting like an antenna that is sensitive to the magnetic component of radiated electromagnetic energy. It is precisely because of this effect that there are some radio receiver designs that use a coil wound around a ferrite rod as an antenna. Humbucker (or humbucking) pickups are designed to reduce the effects of stray magnetic fields. An example of a guitar with humbucker pickups is shown in Fig. 2.4a.

A humbucking pickup consists of two coils located side by side that are connected such that they form series-opposing voltage sources when coupled to a stray external magnetic field. The stray magnetic field induced voltages are 180° out of phase and should cancel completely. This is an example of what engineers call *common mode rejection*, a phenomenon we will see again later in the book.

Although voltages induced by external magnetic fields cancel, when a string vibrates over a pair of humbucker pole pieces, the coils produce voltages that add constructively, generating a large output signal. This occurs because the pole pieces in adjacent coils have opposite magnetic polarity. Figure 2.4b, c illustrates the relative polarities of the windings of the humbucker pickup for magnetic field response and string response, respectively.

Often, all four wires of a humbucker are available and for all practical purposes you have two separate pickups sitting side by side. It is the close proximity of the pickups to one another that helps to ensure that stray magnetic fields induce a common mode signal. However, it is important that the coils be connected properly, otherwise it is possible to cause string vibration signals to cancel, while stray magnetic field induced signals will add constructively. Check the data sheet for your particular pickups for recommended connections, color coding, etc.

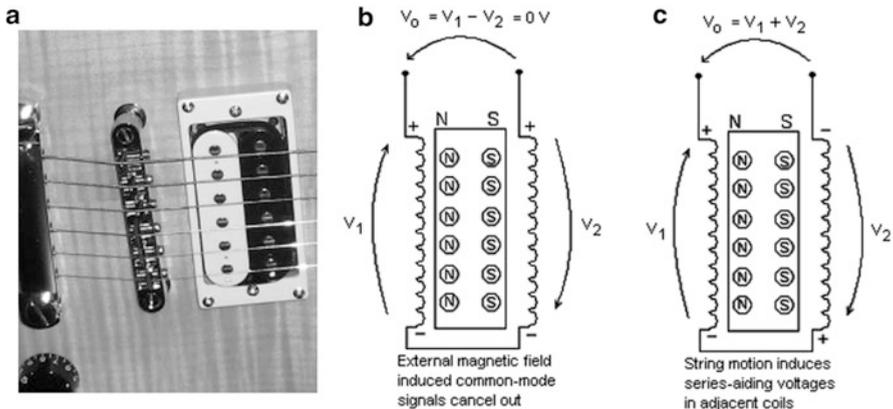


Fig. 2.4 Humbucker pickup and response to external magnetic field vs. string induced signal

Peak and Average Output Voltages

Because there are two coils in series per pickup, humbuckers tend to produce higher amplitude output signals on average than single-coil pickups. As a general rule of thumb, the initial peak amplitude of a typical single-coil pickup will usually be in the range of 200–500 mV, while a humbucker will probably range from 400 to 1,000 mV or more.

Although the initial amplitude of the signal produced by the pickup may be relatively large, the average voltage is likely to be about 20–25% of the peak value. Also, the output will drop off quickly after the initial pluck of the string.

The oscilloscope traces shown in Fig. 2.5 were produced using a Gibson Les Paul Standard guitar, using the neck pickup (490R), volume and tone controls set to maximum (full clockwise).

Comparing the signals in Fig. 2.5 with those shown in Fig. 2.3, we find that for the open A string the single-coil pickup gives us $V_o = 198 \text{ mV}_{\text{P-P}}$, while the humbucker produces $V_o = 488 \text{ mV}_{\text{P-P}}$; about 146% greater voltage. The humbucker also appears to generate a signal that has a more pronounced second harmonic content. We can't really make generalizations based on this single comparison, but this does help explain the differences in tonal quality between humbuckers and single-coil pickups. The difference between the single-coil and humbucker for the barre chord A is even more pronounced, as seen when we compare Fig. 2.3b with Fig. 2.5b.

The physical height of a pickup is usually adjustable, with the pickup suspended in the guitar body by springs and screws. Pole pieces are also sometimes threaded so that individual spacing from strings may be varied. Moving a pole closer to a string results in a larger output signal, but since the poles are magnetic, if a string is located too close it could be pulled into that pole.

The type of magnet used in the construction of a pickup will also influence the amplitude of the output signal. Generally, the stronger the magnets used, the greater the output amplitude will be. Traditionally, pickup magnets were made from ceramic or Alnico, but some newer high-output pickups use more powerful rare-earth magnets.

It is important to keep in mind that guitar signals are extremely dynamic, and they are dependent on hard-to-control variables such as fret finger pressure, pick stiffness, pick force, finger-picking vs. strumming, etc., but all things being equal, humbuckers will produce larger output signals than single-coil pickups.

More Magnetic Pickup Analysis

Let's take a look at (2.1) again. In case you forgot it, here it is

$$V = N \frac{d\Phi}{dt} \quad (2.1)$$

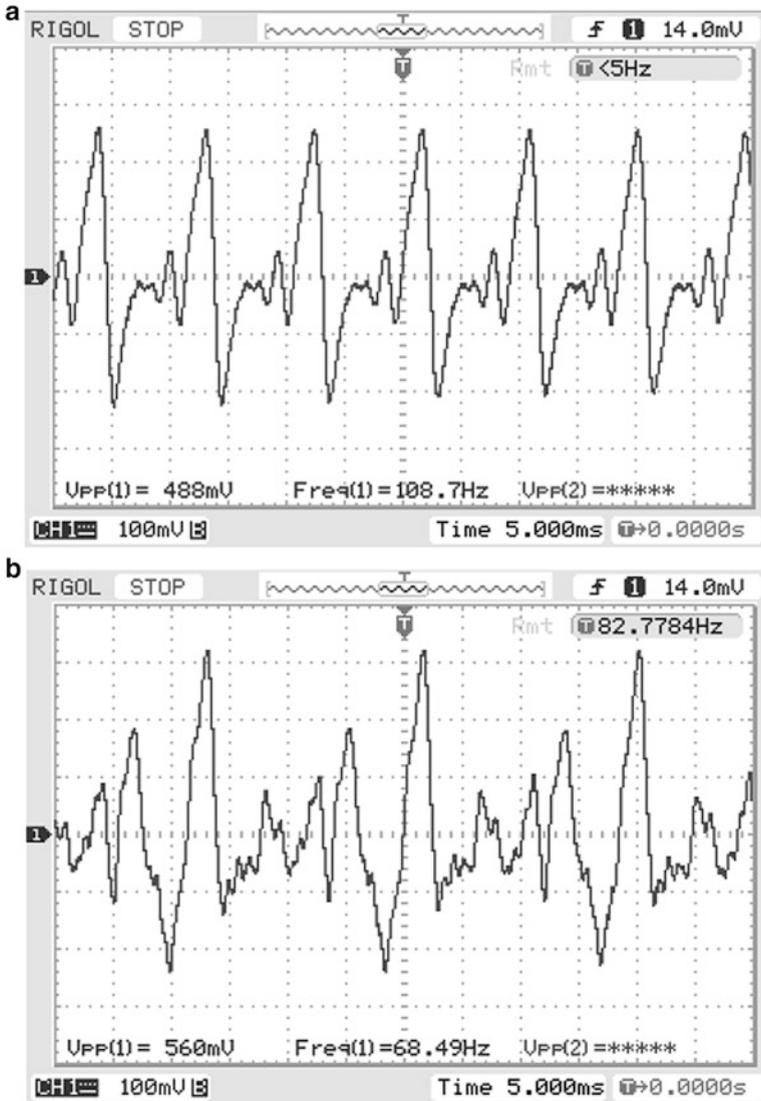


Fig. 2.5 Waveforms from a Les Paul Standard with humbuckers. (a) Open A string. (b) Barre chord A

The ideal magnetic pickup is simply an inductor. In practice, however, because the coil consists of thousands of turns of thin wire, there is significant winding resistance. Comparing to a single-coil pickup a humbucker has a larger N value (more turns of wire), and so produces a greater output voltage.

Inductance

The inductance L , in Henrys, of a pickup coil (which we will approximate as being a solenoid or cylinder) is given by

$$L = \frac{\mu N^2 A}{\ell} \quad (2.2)$$

where μ is the permeability of the pole pieces (H/m), N is the number of turns of wire, A is the cross-sectional area of a pole piece (m^2), and ℓ is the total length of the pole pieces (m). This formula can be used to give a rough estimate of inductance, should you decide to wind your own pickups from scratch.

Inductance values for single-coil pickups typically range from 1 to 5 H. Humbuckers average a little higher, ranging from about 4 to 15 H.

A Pickup Winding Example

Let's use (2.2) to determine the number of turns of wire needed to produce a single-coil pickup like that shown in Fig. 2.2, with $L = 5$ H. Based on measurements of a Stratocaster pickup coil, we get the following physical dimensions:

Pole piece radius, $r = 2.184$ mm (0.002184 m)

Total pole piece length, $\ell = 10$ mm (0.1 m)

The cross-sectional area of a given pole piece is

$$\begin{aligned} A &= \pi r^2 \\ &= (3.14159)(0.002184^2) \\ &= 1.498 \times 10^{-5} \text{ m}^2 \end{aligned}$$

Let's assume the pole piece magnets have approximately the same permeability as electrical steel, which is

$$\mu = 8.75 \times 10^{-4} \text{ H/m}$$

Now, we solve (2.2) for N and plug in the various numbers, which gives us

$$\begin{aligned} N &= \sqrt{\frac{\ell L}{\mu A}} \\ &= \sqrt{\frac{0.1 \times 5}{0.000875 \times 0.00001498}} \\ &= 6,176 \text{ turns} \end{aligned}$$

Table 2.1 Common copper pickup wire gauge data

Gauge	Ω/ft	Diameter (in.)
40	1.08	0.0031
41	1.32	0.0028
42	1.66	0.0025
43	2.14	0.0022

The length of the wire can be estimated as follows. Approximating the pickup as being a rectangle measuring 0.5×2.5 in., the length of wire per turn (d) is the perimeter of the rectangle

$$\begin{aligned} d &= 0.5 + 0.5 + 2.5 + 2.5 \\ &= 6 \text{ in./turn} \end{aligned}$$

So, the total length d_{total} of the wire is approximately

$$\begin{aligned} d_{\text{total}} &= (6 \text{ in./turn})(6,176 \text{ turns}) \\ &= 37,056 \text{ in.} \\ &= 3,088 \text{ ft} \end{aligned}$$

Winding Resistance

There are practical limits to how much wire we can wrap around a pickup. To get more turns, we must use thinner wire, which is more fragile and has higher resistance per unit length. The diameter and resistance data for some common pickup wire gauges is given in Table 2.1. For comparison, consider that a typical human hair is about 0.003 in. in diameter.

We can use this data to determine the winding resistance of the pickup we just looked at. Assuming that we used 43 gauge wire, the resistance of the pickup is

$$\begin{aligned} R &= (2.14 \Omega/\text{ft})(3,088 \text{ ft}) \\ &= 6.6 \text{ k}\Omega \end{aligned}$$

Typical single-coil pickups have winding resistances in the 5–7 k Ω range, while humbuckers typically range from 6 to 20 k Ω .

Winding Capacitance

Any time conductors are separated by a dielectric (insulating) material, a capacitor is formed. The many turns of wire in a pickup, separated by the thin enamel insulation, will result in capacitance that is distributed through the coil. The more

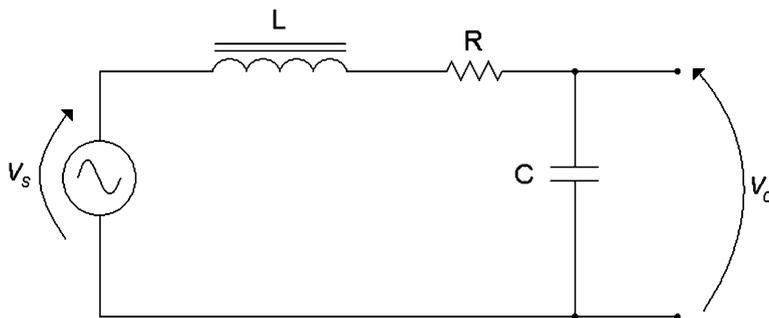


Fig. 2.6 Approximate model for magnetic pickup

turns of wire, the greater this interwinding capacitance will be. Interwinding capacitance is difficult to predict, but measurements made in the lab for several different single-coil and humbucker pickups averaged about 100 pF for single coils and 200 pF for humbuckers.

Approximate Circuit Model for a Magnetic Pickup

All of the magnetic pickup parameters discussed previously can be combined to form the model shown in Fig. 2.6. The pickup model turns out to be a second-order, low-pass filter.

It's interesting to analyze this pickup model using representative values for single-coil and humbucker pickups. Using PSpice to simulate the pickup circuit using the various R , L , and C values, we obtain the frequency response curves in Fig. 2.7. The circuit component values used and peak frequency parameters are

$$\text{Single-coil: } R = 5 \text{ k}\Omega, \quad L = 2 \text{ H}, \quad C = 100 \text{ pF}$$

$$f_{\text{pk}} = 9.2 \text{ kHz}, \quad A_{\text{pk}} = 27 \text{ dB}$$

$$\text{Humbucker: } R = 15 \text{ k}\Omega, \quad L = 10 \text{ H}, \quad C = 200 \text{ pF}$$

$$f_{\text{pk}} = 3.6 \text{ kHz}, \quad A_{\text{pk}} = 23 \text{ dB}$$

These response curves have very large peaks, which occur at the resonant frequency of the circuit. Low-pass (and high-pass) filters that exhibit peaking are said to be *underdamped*. Also, because these are second-order LP filters the asymptotic response rolls off at -40 dB/decade once we pass the peak frequencies and enter the stopband. In general, the rolloff rate m of an n th order filter will be given by

$$m = \pm 20n \text{ dB/decade} \quad (2.3)$$

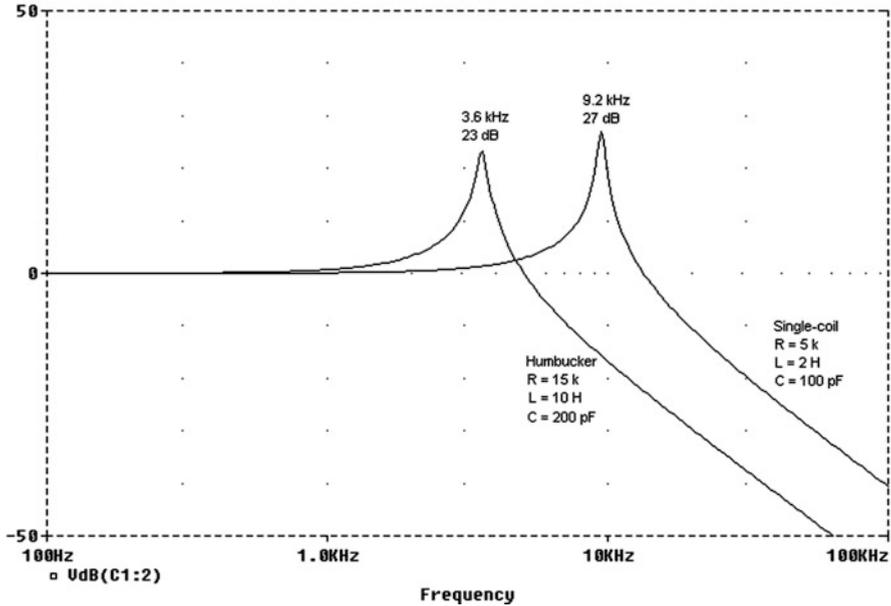


Fig. 2.7 Frequency response for representative single-coil and humbucker pickups

The response curves of Fig. 2.7 are only valid for these pickups without volume or tone control circuitry and with no external cable connected. These factors can alter pickup response dramatically. We will come back to this topic again after the next section.

Piezoelectric Pickups

Piezoelectric pickups convert strain caused by mechanical vibrations into an electrical signal. Most piezoelectric pickups are constructed of a ceramic material such as barium titanate ($BaTiO_3$), which may be mounted on a thin metal disk that is glued to the guitar soundboard or built into the bridge assembly.

Piezoelectric pickups are best suited for use with acoustic and hollow body electric guitars, where vibration of the body has significantly high amplitude. Normally, the highest signal levels are obtained with the pickup mounted near the bridge. For experimental purposes, a piezo pickup was mounted in several locations on the outside of an acoustic guitar as shown in Fig. 2.8. Internal mounting would be preferred simply to protect the pickup from damage, but the function of the pickup is the same either way. The pickup shown here is a Schatten soundboard transducer.

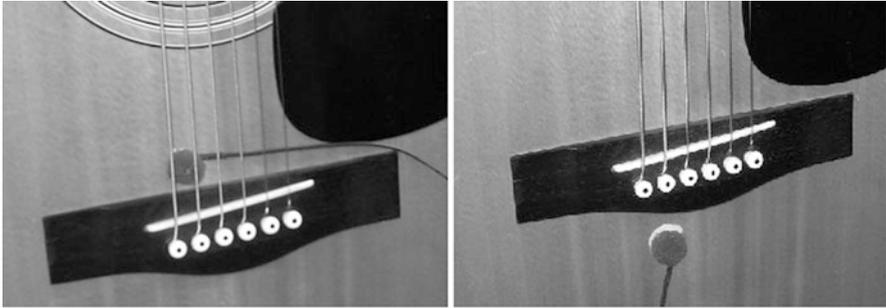


Fig. 2.8 Piezoelectric pickup on an acoustic guitar

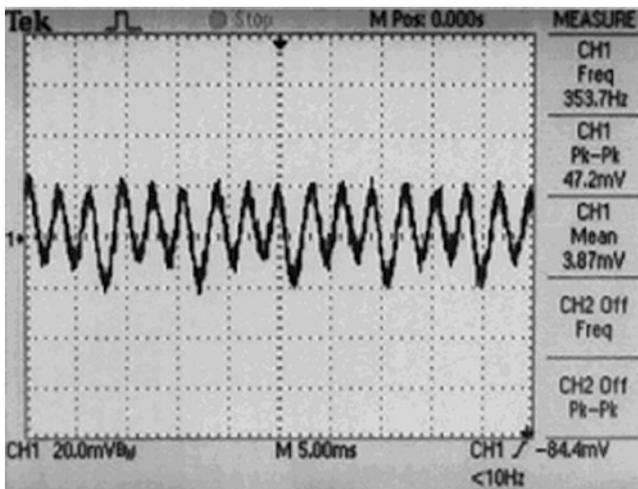


Fig. 2.9 Piezoelectric signal from acoustic guitar. Open A (110 Hz)

An oscilloscope trace for the acoustic guitar with the piezo pickup mounted as shown on the left side of Fig. 2.8 is shown in Fig. 2.9. The open A string was picked, and measuring the time interval between the large negative peaks, the period is close to 110 Hz; however, there is very strong third harmonic present as well. Note that the output voltage produced by the piezo pickup (driving a scope probe with 10 M Ω resistance) is about one-tenth of that produced by the average magnetic pickup; 47 mV_{P-P} vs. 488 mV_{P-P} for the humbucker in Fig. 2.5a.

Piezoelectric Pickup Analysis

Whenever two conductors are separated by an insulator, a capacitor is formed. It turns out that the physical structure of a piezoelectric pickup is essentially the same as that of a ceramic capacitor except that as noted before, the dielectric

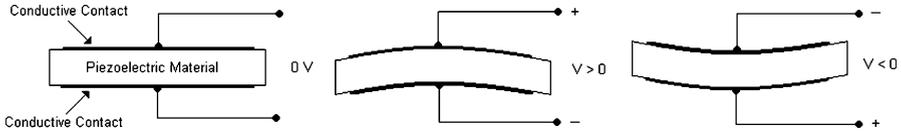


Fig. 2.10 Deformation of piezoelectric material generates a voltage

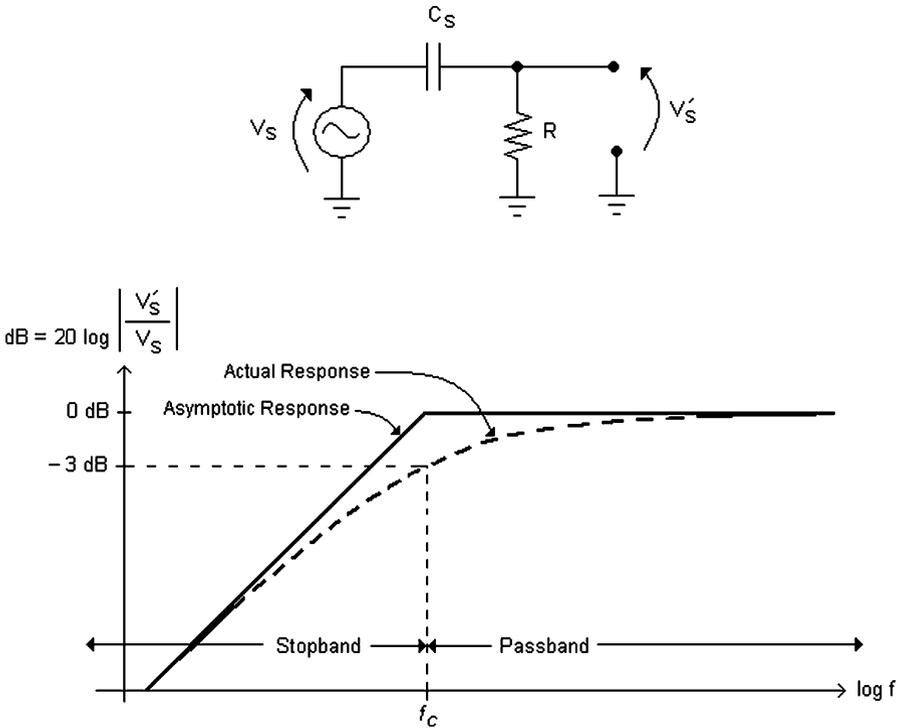


Fig. 2.11 Equivalent circuit for piezo pickup connected to external resistance, and frequency response curve

insulator is made of a material that will generate a voltage when subjected to mechanical strain. This is shown in Fig. 2.10.

A useful approximate circuit model for a piezo pickup is simply a voltage source with a series capacitance. The capacitance will range from around 500 to 1,200 pF for typical piezo pickups. The peak output voltage generated by a single pickup will generally be around 50–100 mV under typical loading conditions. When the pickup is connected to a load such as the input of an amplifier, a first-order, high-pass (HP) filter is formed. This is shown in Fig. 2.11.

The corner frequency of the equivalent high-pass filter is given by the same equation as that of the low-pass filter covered in Chap. 1, which is given as follows:

$$f_C = \frac{1}{2\pi RC_S} \quad (2.4)$$

where C_S is the capacitance of the piezo source and R is the resistance being driven by the pickup. It is important that R be large enough to ensure that the lowest frequencies produced by the guitar are within the passband of the filter's response. For the HP filter, the higher the value of R the lower f_C becomes.

Example Calculation: Input Resistance and Corner Frequency

If we connect a piezo pickup with $C_S = 1,000$ pF to an amplifier with input resistance $R_{in} = 100$ k Ω , the lowest frequency we can effectively amplify is

$$\begin{aligned} f_C &= \frac{1}{2\pi RC_S} \\ &= \frac{1}{(2\pi)(100 \text{ k}\Omega)(1,000 \text{ pF})} \\ &= 1.6 \text{ kHz} \end{aligned}$$

We have a bit of a problem here. The open low E string frequency, E2, is about 81 Hz, which is so far into the stopband of this filter that response would be down about -50 dB. This is clearly not acceptable. The input resistance of the amplifier must be much higher if we want to pass frequencies down to 81 Hz. Solving (2.4) for R lets us calculate the required resistance.

$$R = \frac{1}{2\pi f_C C_S} \quad (2.5)$$

Using the values $f_C = 81$ Hz and $C_S = 1,000$ pF we get

$$R = 1.9 \text{ M}\Omega$$

This is a very high resistance: higher than the typical input resistance of a guitar amplifier. Further complicating the situation are the effects of amplifier input capacitance and the characteristics of the cable that connects to the amplifier. These factors would have major negative effects on the signal.

Guitar cords are shielded coaxial cables, usually consisting of an outer braided copper shield surrounding a center conductor. The resistance of this type of cable is negligibly small, but the capacitance can be significant. The longer the cord, the greater its capacitance will be. Typical cord capacitances range from about 50 to 150 pF/m. This would have to be factored into an analysis of the piezo pickup.

There are other factors that further complicate the situation. If we were to add passive volume and tone controls, the piezo pickup would be loaded so heavily that it would be useless. And, even if we left out the tone controls, the inherently high-output impedance of the piezo pickup would make the whole system very sensitive to cable microphonics and external noise pickup.

We could perform some more calculations, but that would only confirm that what most of you probably already know; piezoelectric pickups require the use of a preamplifier. The preamplifier or just “preamp” serves as a buffer between the pickup and the cord/amplifier. The preamp will normally be located inside the guitar itself and may also have built-in tone/equalizer circuitry. We will take a detailed look at these types of amplifiers in the next chapter.

Sometimes, multiple piezo pickups will be mounted at various locations around the soundboard. If the pickups are connected in series, a much larger output signal will be generated. However, the series connection results in lower equivalent capacitance at the output of the pickups, requiring a higher input resistance for the preamp to get good low frequency response.

Piezo pickups could also be connected in parallel. This does not increase output voltage, but does increase the equivalent capacitance at the output. This allows lower preamp input resistance to be used while still maintaining good low frequency response.

Both series and parallel approaches will alter the frequency response of the system. In general, the series connection will raise the lower corner frequency, producing a brighter sound, while the parallel connection will decrease the lower corner frequency, enhancing bass response.

There will be certain positions on the soundboard where vibration is maximized, due to resonance of the guitar at different frequencies. Using different series/parallel connections of multiple pickups at various locations allows response to be tailored to suit individual preferences.

Guitar Volume and Tone Control Circuits

Volume and tone controls generally interact so strongly with one another and with pickups that they can't really be considered as separate components in most guitars. We will start by looking at typical examples of each and then connect them and see how they behave as a whole.

Potentiometers

A potentiometer, often simply called a “pot,” is a three-terminal variable resistor. The schematic symbol for a pot and several different variations are shown in Fig. 2.12. The center terminal of the pot is called the *wiper*. The pot of Fig. 2.12b

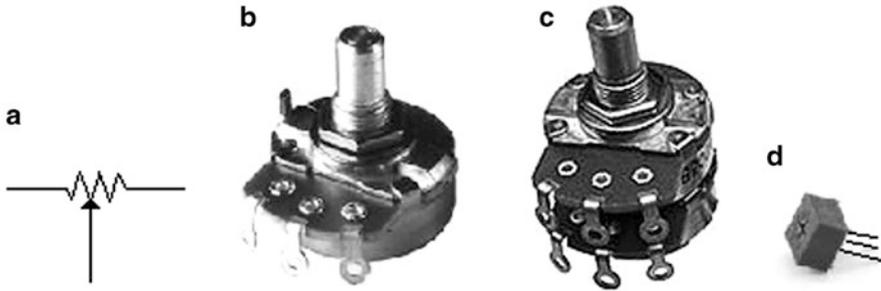


Fig. 2.12 Potentiometer symbol and common packages

is a typical single-turn unit. Figure 2.12c is a dual gang pot; it is basically two separate pots with a common shaft. These are useful in stereo audio applications. A trim pot is shown in Fig. 2.12d. Trim pots are usually mounted on a printed circuit board (PCB). A standard potentiometer will usually rotate through about 300° from end to end, although multi-turn pots are also available.

The schematic diagram of Fig. 2.13a shows a potentiometer connected as a volume control, which is really a variable voltage divider. A pictorial wiring diagram is shown in Fig. 2.13b. In this circuit, as the shaft is rotated clockwise the output voltage varies from minimum ($V_o = 0\text{ V}$) to maximum ($V_o = V_{in}$). The output voltage is given by the voltage divider equation

$$V_o = V_{in} \frac{R_B}{R_A + R_B} \quad (2.6)$$

Potentiometer Taper

The *taper* of a potentiometer defines the way its resistance varies as a function of shaft rotation. A *linear taper* potentiometer will produce the characteristic curve of Fig. 2.13c, where the output voltage is a linear function of shaft rotation.

An *audio taper* potentiometer will produce the curve of Fig. 2.13d, where the output voltage is exponentially related to shaft rotation. This is a useful characteristic for volume control applications because the sensitivity of human hearing is logarithmic. The complementary relation between hearing sensitivity and the audio taper transfer characteristic results in a perceived linear relationship between pot shaft rotation and loudness of the sound.

There are other potentiometer tapers available, including antilog (also called inverse log) and S-taper, but they are not of particular interest in our applications.

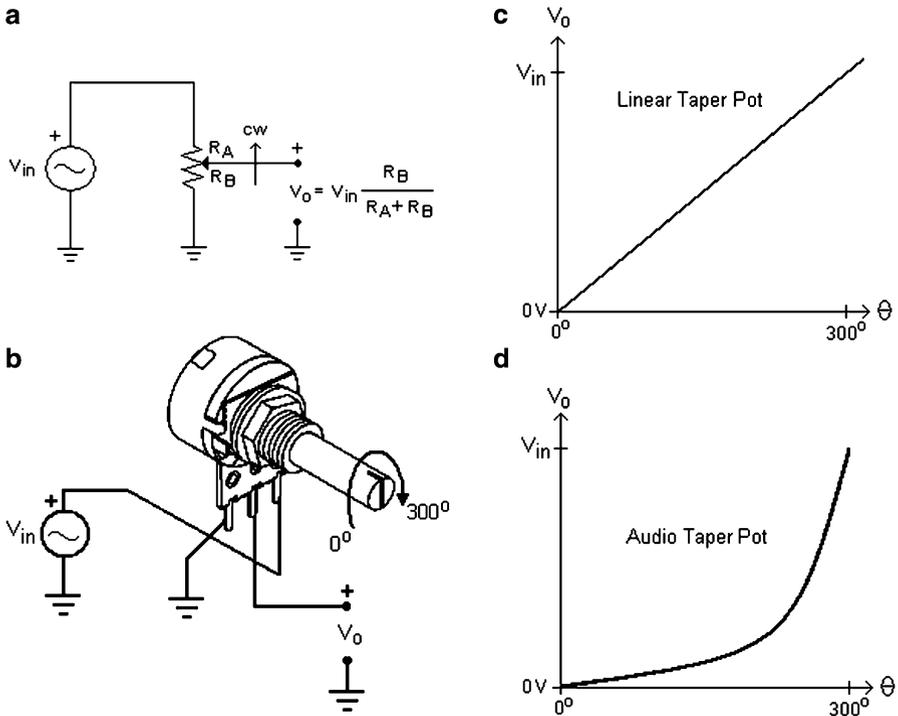


Fig. 2.13 (a, b) Potentiometer volume control. (c) Linear taper characteristic. (d) Audio taper characteristic

Transfer Function

The output/input characteristic of a network is called its *transfer function*. The concept of the transfer function is not critical to understanding how a volume control works, but I thought it wouldn't be a bad idea to introduce this somewhat abstract concept early on.

For a voltage divider, the output and input variables are V_o and V_{in} . Dividing both sides of (2.6) by V_{in} gives us the transfer function of the potentiometer

$$\frac{V_o}{V_{in}} = \frac{R_B}{R_A + R_B} \tag{2.7}$$

When you come right down to it, a volume control is simply a variable voltage divider. Audio taper potentiometers are best suited for use as volume controls because they make the perceived loudness of the signal change as a linear function of shaft rotation. Before we leave the topic of potentiometers, there is one more common use that we will discuss. That is, using the pot as a simple variable resistor.



Fig. 2.14 Common symbol used for a variable resistor or rheostat

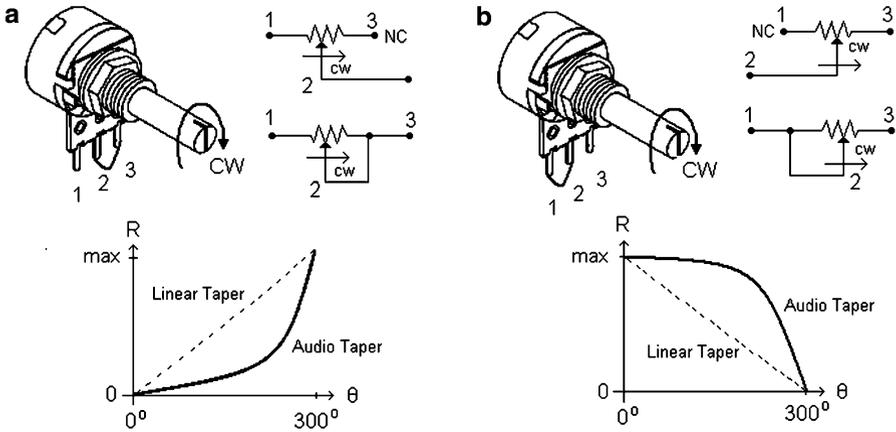


Fig. 2.15 Connecting a potentiometer as a rheostat

Rheostats

A potentiometer can also be used as a simple variable resistor, in which case the pot is functioning as a *rheostat*. Often a rheostat will be drawn schematically as shown in Fig. 2.14.

A pot can serve as a rheostat simply by using the wiper and either end terminal. The unused end may be left open or it may be shorted to the wiper as shown in Fig. 2.15.

Connecting the pot as shown in Fig. 2.15a causes the resistance to increase as the shaft is turned clockwise. For an audio taper pot, the resistance increases exponentially. Connecting the pot as shown in Fig. 2.15b causes the resistance to decrease as the shaft is turned clockwise.

Potentiometers are available with different power dissipation ratings. For the typical volume and tone control applications, inexpensive half-watt potentiometers are more than adequate.

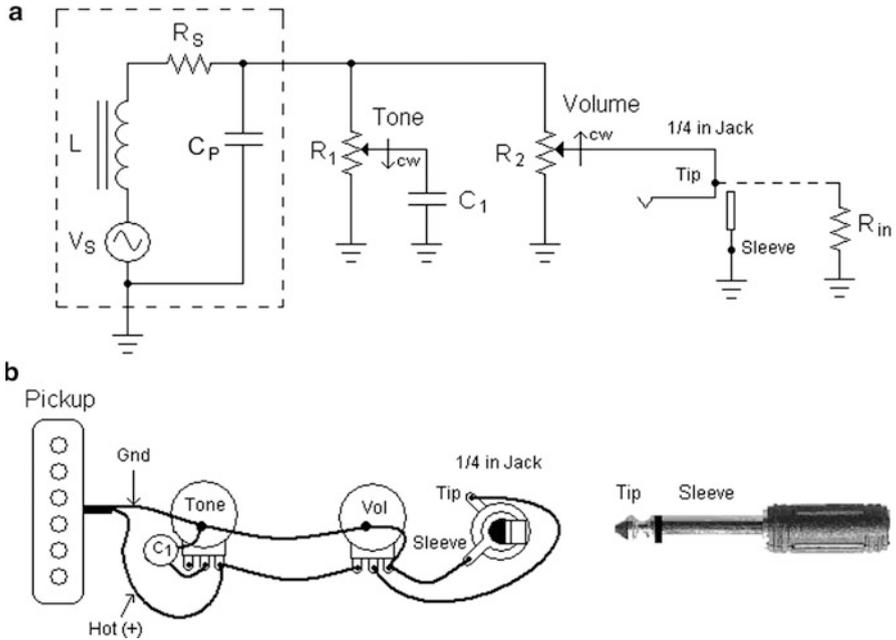


Fig. 2.16 Common volume/tone control schematic and pictorial wiring diagram for single-coil pickup

Basic Guitar Tone Control Operation

We have already covered a lot of the background information necessary to understand the operation of a tone control. Tone controls can be quite complex, but those found in the guitar itself are usually simple, adjustable low-pass filters.

A very common circuit used to implement volume and tone controls is shown in Fig. 2.16. Resistor R_S is the series winding resistance of the magnetic pickup. This resistance will usually range from 5 to 10 k Ω for a single-coil pickup and may be up to 20 k Ω or more for series connected humbuckers. The values of the potentiometers are normally chosen to be about ten times higher than R_S in order to prevent heavy loading of the pickup. Common potentiometer values used in guitars typically range from 250 k Ω to 1 M Ω . Notice that the tone control is connected as a rheostat, while the volume control is a true potentiometer (voltage divider). Both pots should have audio taper characteristics.

The input resistance, R_{in} , of the amplifier to which the guitar is connected will have an effect on the response of the pickup. This is shown connected via the dashed line at the right side of the schematic. Typical input resistance values for vacuum tube based amplifiers range from 250 k Ω to 1 M Ω . The effects of cable capacitance and resistance will be neglected here.

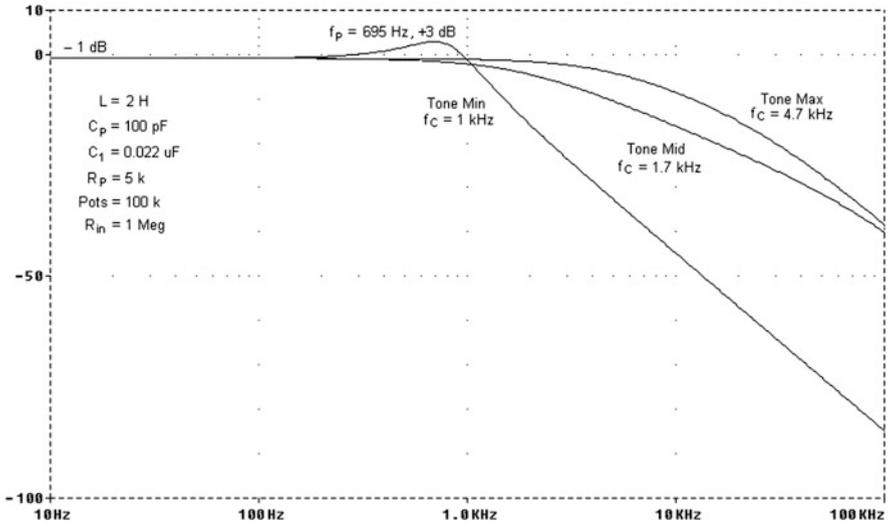


Fig. 2.17 Frequency response of circuit in Fig. 2.16 with 100 kΩ pots

It is certainly possible to perform an analysis of this circuit by hand, but it would fill a few pages or so with phasor algebra, and it wouldn't make for very interesting reading. Instead, the circuit was simulated using PSpice to determine its frequency response. The circuit in Fig. 2.16 uses a single-coil pickup, which was simulated using the following component values.

$$R_S = 5 \text{ k}\Omega, \quad R_1 = R_2 = 100 \text{ k}\Omega, \quad R_{in} = 1 \text{ M}\Omega, \quad L = 2 \text{ H}, \\ C_P = 100 \text{ pF}, \quad \text{and} \quad C_1 = 0.022 \text{ }\mu\text{F}$$

Examination of the curves in Fig. 2.17 indicates that with the tone control set for maximum resistance (full CW rotation), the response is flat at -1 dB up to the corner frequency of 4.7 kHz .

At mid-rotation, the frequency response is flat at -1 dB until the corner frequency at 1.7 kHz . At minimum tone control resistance (full ccw) the network becomes underdamped, with a peak of $+3 \text{ dB}$ at 695 Hz .

Increasing the value of the potentiometers such that $R_1 = R_2 = 500 \text{ k}\Omega$ produces the response plot in Fig. 2.18. The increased peaking at both extremes of pot rotation indicate that high frequency response is improved somewhat when higher resistance pots are used.

The graph of Fig. 2.19 shows the response for the tone control circuit using $C_1 = 0.022 \text{ }\mu\text{F}$, $500 \text{ k}\Omega$ pots, and a humbucking pickup with $L = 10 \text{ H}$, $R_S = 15 \text{ k}\Omega$, and $C_S = 200 \text{ pF}$. The higher inductance of the humbucker results in shifting of the curves toward lower frequencies.

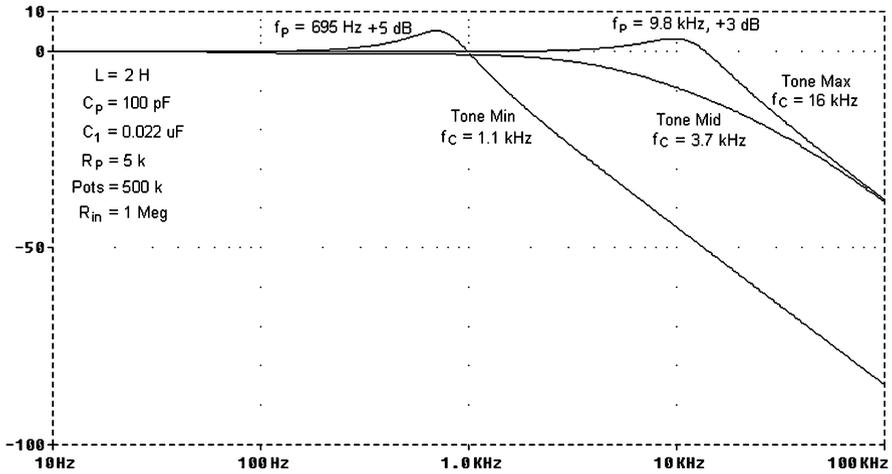


Fig. 2.18 Tone control response with 500 kΩ pots

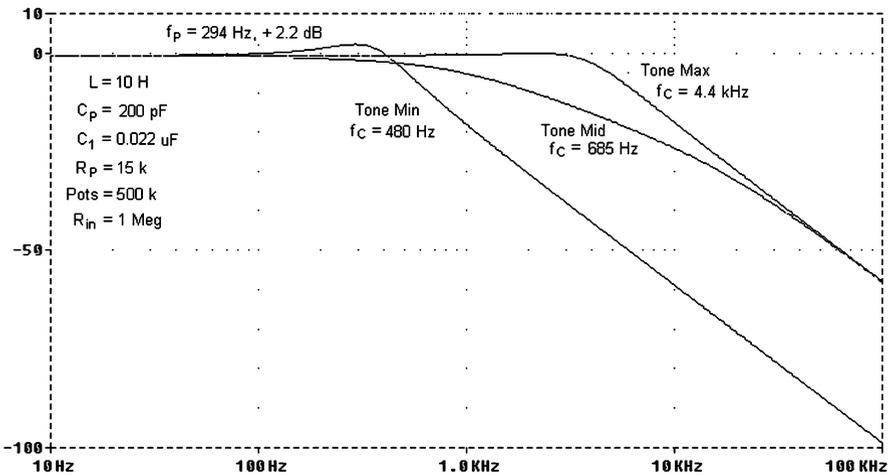


Fig. 2.19 Typical humbucker response

You can experiment with different values of C_1 in the circuit to change the response of the tone control. Using a larger capacitor value, say $C_1 = 0.047 \text{ }\mu\text{F}$, will lower f_c . A smaller value such as $C_1 = 0.01 \text{ }\mu\text{F}$ will increase f_c .

Multiple Pickups

A guitar with two pickups could be wired as shown in Fig. 2.20. This is really just a duplication of the circuit in Fig. 2.16 where we have independent volume and tone controls for each pickup. With the switch in position 1, the neck pickup drives the output. Position 2 connects both pickups in parallel, while position 3 connects the bridge pickup to the jack.

Pickup Phasing

You may have wondered why I placed plus signs at the ends of the pickup coils in some of the schematic diagrams. These plus signs simply indicate the relative phase of the coils. Different tone characteristics can be obtained by connecting guitar pickups in and out of phase with each other. The basic two-pickup circuit, with phase reversal, is shown in Fig. 2.21. When phase switch S_2 is in position 1 the pickups are connected in the normal phase relationship. In position 2 the phase of the bridge pickup is reversed.

Reversing the phase of a pickup will have an audible effect only when both pickups are used at the same time. This occurs because of the change in constructive and destructive interference relationships between various harmonic components produced in each pickup.

If we add a third pickup, the number of possible wiring configurations increases dramatically. This is especially true if humbuckers are used in nonstandard configurations.

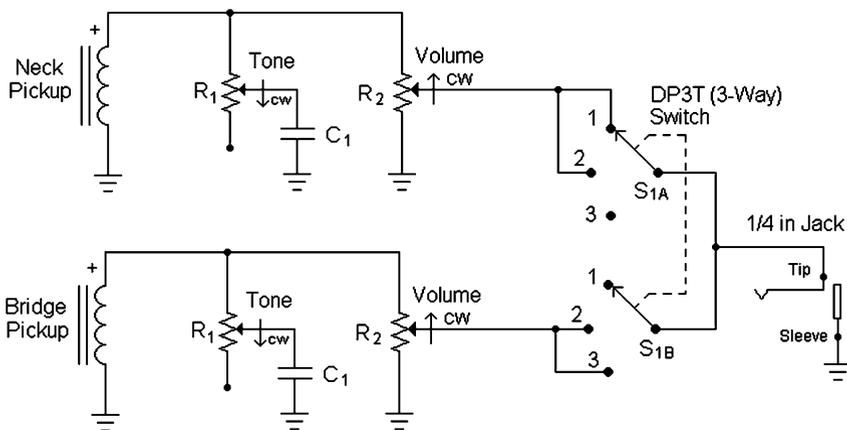


Fig. 2.20 Wiring for two pickups with independent volume and tone controls

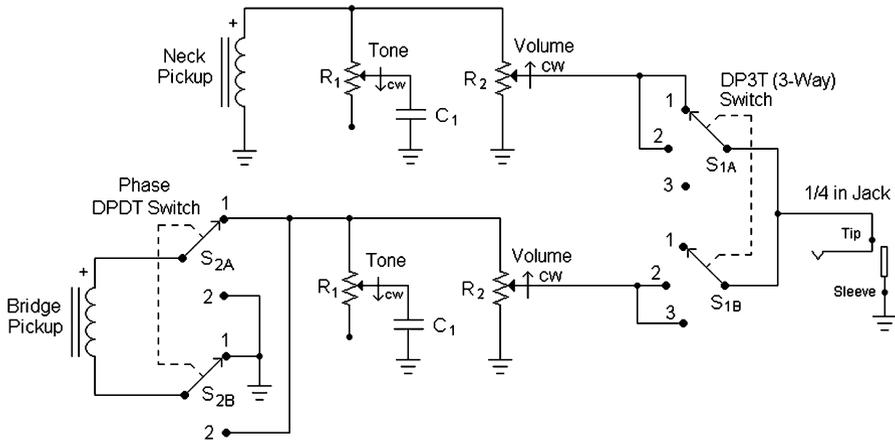


Fig. 2.21 Reversing the relative phase of two pickups

Amplifier Tone Controls

Although amplifiers are the topic of the next chapter, this is as good a place as any to start a discussion on tone control circuits. Practical amplifiers consist of several gain stages and a power output stage. Volume and tone controls are usually located between stages as shown in Fig. 2.22.

A Basic Tone Control Circuit

One of the simplest tone controls is the variable filter shown in Fig. 2.23. This is really just a low-pass or treble-cut filter and is the same basic tone control that is used in many guitars, as shown in Fig. 2.16. In this circuit R_o is the output resistance of the driving stage and R_{in} is the input resistance of the driven stage. The potentiometer is normally chosen to be greater in value than the output resistance in order to minimize loading, which would reduce the overall signal level. Depending on actual circuit values, insertion loss for this tone control typically ranges from 2 to 6 dB (a factor of 0.8–0.5).

When the wiper is at the bottom of the pot (fully clockwise) R_1 is at maximum resistance and the filter has little effect on the signal, even at high frequencies where $|X_C|$ is very small. When the wiper is set to the upper side of the pot, $R_1 = 0 \Omega$, and the capacitor tends to shunt higher frequencies to ground, cutting the treble response. The response curves shown in Fig. 2.23 were produced using component values that would be typical for vacuum tube amplifiers.

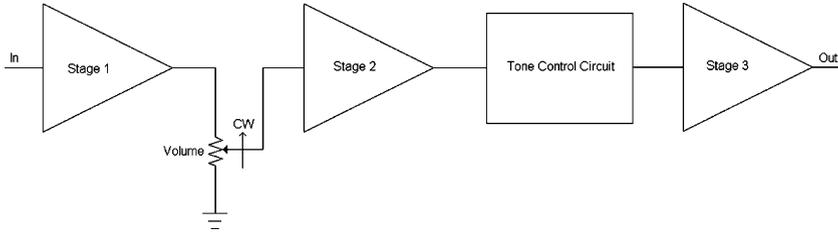


Fig. 2.22 Typical volume and tone control locations in a guitar amplifier

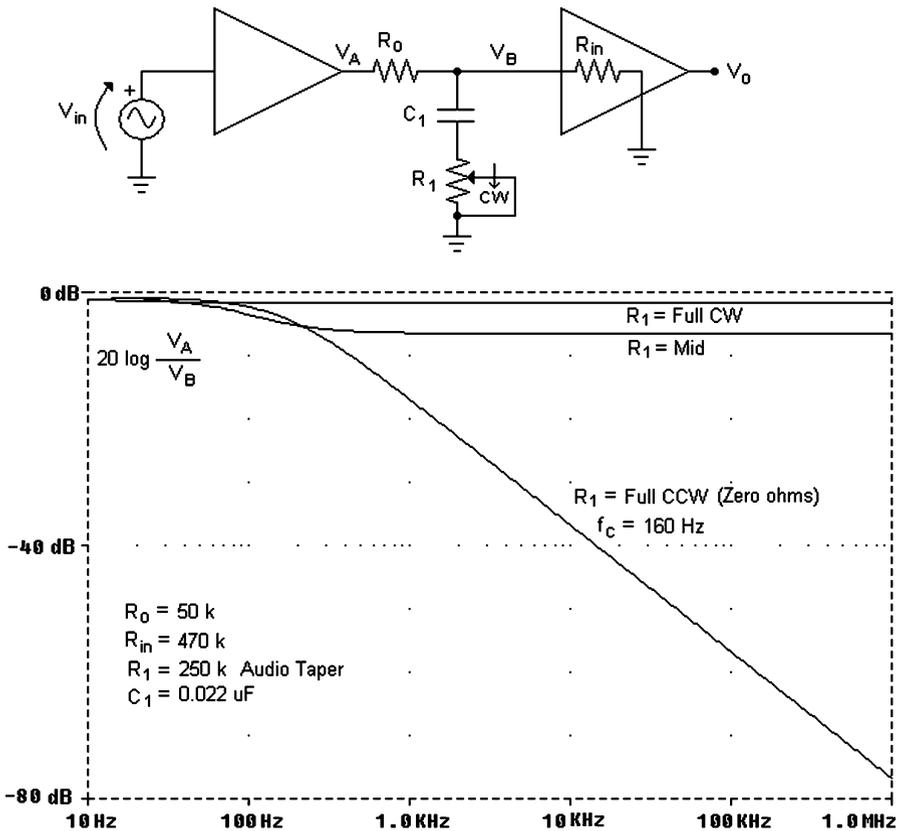


Fig. 2.23 Simple tone control circuit and frequency response plot

It is interesting to note that when the pot is at mid-rotation treble is down by 6 dB for frequencies above 200 Hz. When the response of a filter drops initially and then levels off, this is called a *shelving response*.

The corner frequency of the filter can be shifted to higher or lower frequencies by changing the value of C_1 . If a brighter overall sound is preferred, the corner

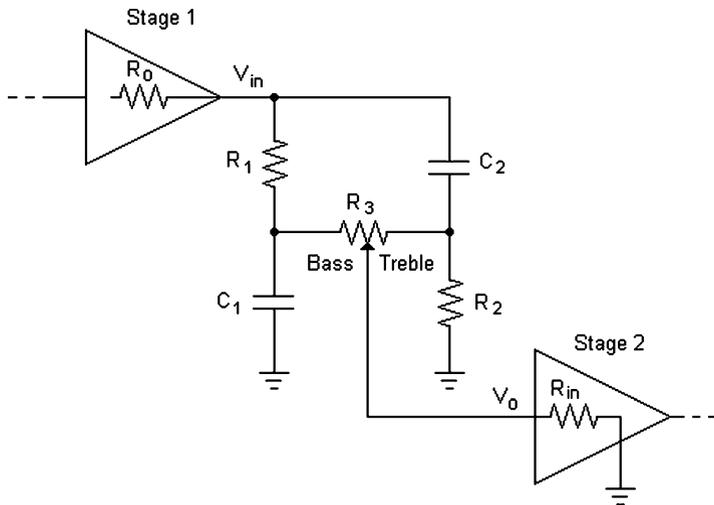


Fig. 2.24 Improved single-potentiometer tone control

frequency of the filter can be increased by using a smaller capacitor. For example, using $C_1 = 0.01 \mu\text{F}$ moves the corner frequency up to $f_c \cong 350 \text{ Hz}$.

Increasing the capacitor to $C_1 = 0.033 \mu\text{F}$ results in $f_c \cong 100 \text{ Hz}$. With the pot set for $R_1 = 0 \Omega$ (max counter clockwise), the corner frequency is given by a modified version of the first-order RC filter equation, which is

$$f_c = \frac{1}{2\pi(R_o || R_{in})C_1} \tag{2.8}$$

Improved Single-Pot Tone Control

The tone control of Fig. 2.23 is simple but its performance is not very good. The tone control in Fig. 2.24 combines HP and LP filters which allow for adjustment of both bass and treble frequency ranges.

In this circuit, R_1 and C_1 form a low-pass filter, while R_2 and C_2 form a high-pass filter. Potentiometer R_3 allows variable mixing of the outputs of the low- and high-pass filters, which is applied to the next stage of amplification.

A linear potentiometer would be used in this application. As the wiper of the pot is moved to the left, more low frequency signal energy is passed to the output, while the high frequency band is attenuated. Moving the wiper to the right attenuates the low-pass output and allows high frequencies to be passed on to the next stage.

The filter is designed such that the corner frequency of the low-pass section is located near the low end of the guitar frequency range around 100–200 Hz, while

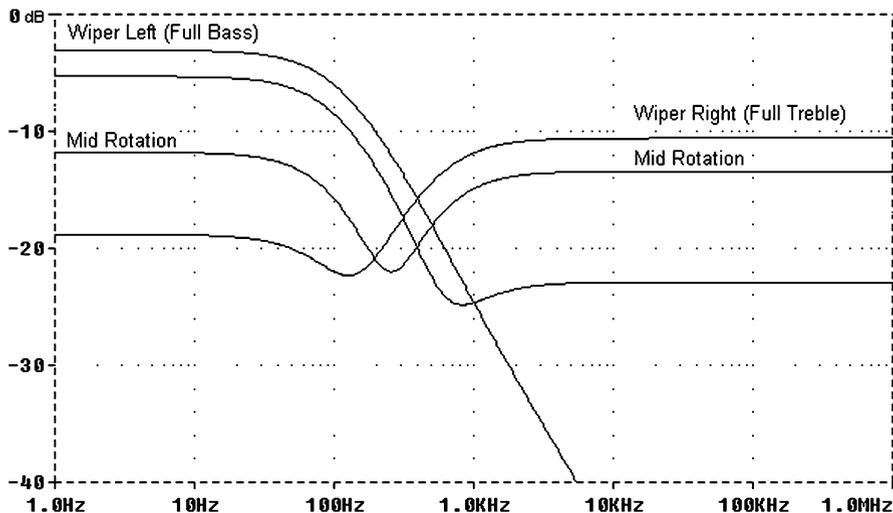


Fig. 2.25 Frequency response of the improved tone circuit

the high-pass filter corner frequency is typically set to around 600–800 Hz or possibly higher. Accurate corner frequency equations for this circuit are very complex, but we can calculate the approximate LP and HP section corner frequencies using the usual first-order RC filter equation.

$$f_{C(LP)} \cong \frac{1}{2\pi R_1 C_1}$$

$$f_{C(HP)} \cong \frac{1}{2\pi R_2 C_2}$$

If you would like to experiment with this tone control, some reasonable starting values for components are

$$R_1 = R_2 = 47 \text{ k}\Omega,$$

$$C_1 = 4,700 \text{ pF},$$

$$C_2 = 0.022 \text{ }\mu\text{F},$$

$$R_3 = 250 \text{ k}\Omega, \quad \text{linear taper pot}$$

A frequency response plot for the circuit, using the component values listed, with $R_o = 50 \text{ k}\Omega$, and $R_{in} = 470 \text{ k}\Omega$ is shown in Fig. 2.25. At mid-rotation of the pot, response is relatively flat, with an insertion loss of about 12 dB. The response dips to about -24 dB at 250 Hz.

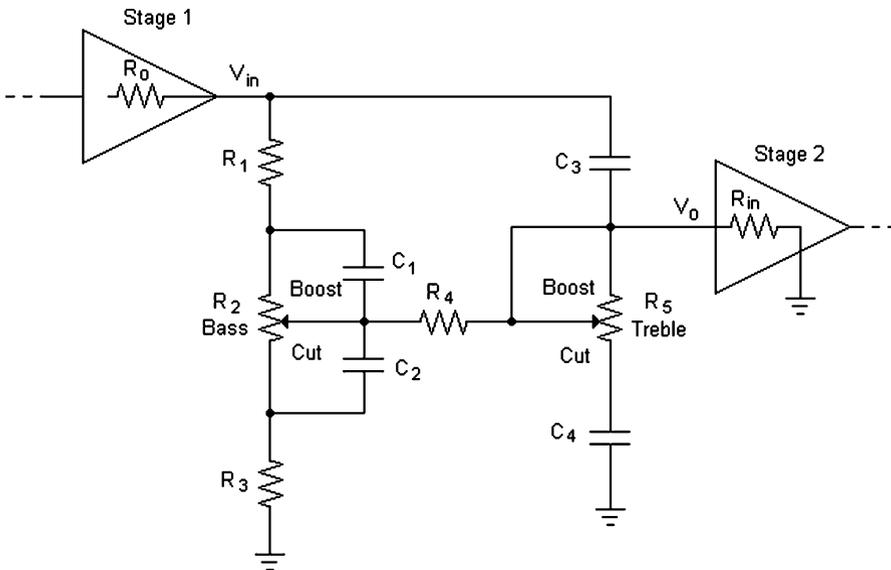


Fig. 2.26 Baxandall tone control circuit

Baxandall Tone Control

The Baxandall tone control is a classic circuit, named after its inventor Peter Baxandall. Variations of the Baxandall tone control circuit are used more predominantly in hi-fidelity amplifiers, but it can also be used in musical instrument amps. The basic Baxandall circuit is shown in Fig. 2.26.

The following component values provide a good starting point for experimentation.

- | | |
|--|-----------------------------|
| $R_1 = 100\text{ k}\Omega$ | $C_1 = 470\text{ pF}$ |
| $R_2 = 250\text{ k}\Omega$ (Audio Taper) | $C_2 = 0.0047\ \mu\text{F}$ |
| $R_3 = 10\text{ k}\Omega$ | $C_3 = 330\text{ pF}$ |
| $R_4 = 150\text{ k}\Omega$ | $C_4 = 0.0033\ \mu\text{F}$ |
| $R_5 = 250\text{ k}\Omega$ (Audio Taper) | |

The frequency response of the circuit is shown in Fig. 2.27, for several settings of the bass and treble controls using the component values listed, assuming $R_o = 50\text{ k}\Omega$ and $R_{in} = 470\text{ k}\Omega$, which are reasonable ballpark values for vacuum tube amplifiers.

With both bass and treble controls set for maximum, the Baxandall circuit has a response of about -6 dB at low and high frequencies, with a dip to about -20 dB at $f = 935\text{ Hz}$. The response is relatively flat at about 23 dB insertion loss with bass and treble controls set to mid-rotation.

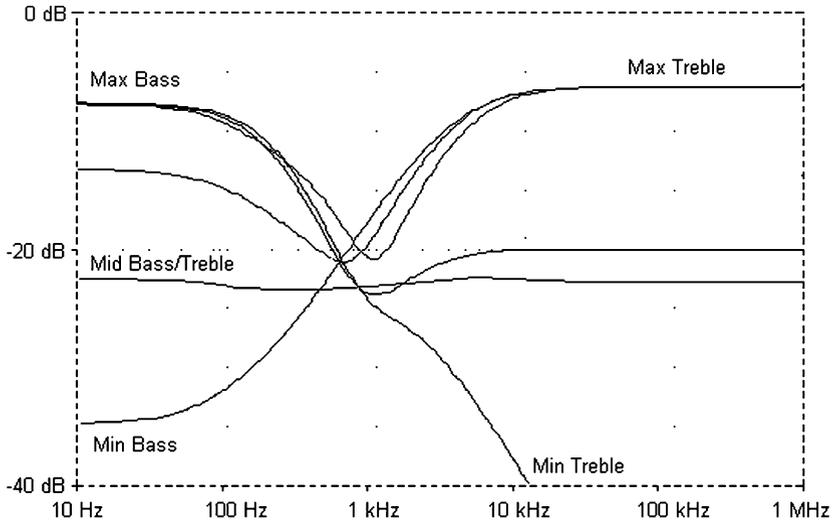


Fig. 2.27 Tone control response for various bass and treble settings

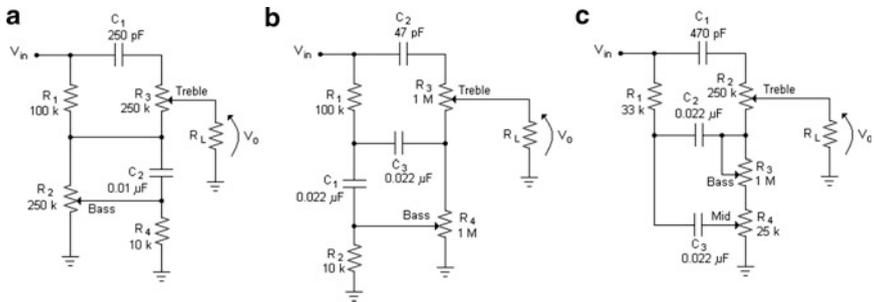


Fig. 2.28 Additional common tone control circuits. (a) Fender type, (b) Vox type, (c) Marshall type

Other Tone Control Circuits

Three final examples of passive tone control circuits are shown in Fig. 2.28. The circuit of Fig. 2.28a is typical of the tone controls used in Fender amplifiers, while Fig. 2.28b is typical of Vox amplifiers. Using the component values shown, both of these tone circuits have an average loss of about 18 dB at midpoint adjustment of the potentiometers. Figure 2.28c is representative of Marshall tone controls. This circuit introduces an average loss of about 10 dB at midpoint adjustment.

Like the tone controls presented earlier, the component values given in these schematics are those that would be used in a typical vacuum tube type amplifier.

Table 2.2 Tone control insertion loss

Tone control	Figures	Insertion loss ^a
Basic treble cut	Fig. 2.23	6dB (0.5)
Single pot	Fig. 2.24	12dB (0.25)
Baxandall	Fig. 2.26	23dB (0.0708)
Fender type	Fig. 2.28a	18dB (0.126)
Vox type	Fig. 2.28b	18dB (0.126)
Marshall type	Fig. 2.28c	10dB (0.316)

^aIf we had specified “insertion gain” then these values would be negative, i.e., -6 dB, -12 dB, etc. The term “insertion loss” implies the negative sign

Generally, the load resistance connected to the tone control will range from 470 k Ω and up.

Tone control circuits can get quite complex, incorporating RLC (resistor–inductor–capacitor) networks, active filters, and specialized integrated circuits. All passive tone controls attenuate the signal to some extent. In general, the more complex the tone control, the greater the loss will be. This loss can be made up for by using an additional gain stage or by incorporating an amplifier into the tone control circuit itself. The insertion loss values in dB and fractional form for the tone controls presented here are summarized in Table 2.2.

Final Comments

This chapter has presented a somewhat minimalist view of pickup configurations and tone control circuitry. There are literally thousands of guitar pickup and tone control variations that can be used. If you are interested in specific pickup wiring diagrams you should check out the Web sites of the major guitar and pickup manufacturers.

The concepts that were presented here will be seen again throughout the following chapters. In Chap. 3 we will use the basic HP filter relationships to determine the frequency response of amplifier coupling and bypass networks. In Chaps. 4 and 6 we will see where tone controls are applied in complete amplifier designs, and in Chap. 5 we will look at some very sophisticated filters when we examine effects circuits such as phase shifters, wah-wahs, and flangers.

Summary of Equations

Lenz's law

$$V = N \frac{d\Phi}{dt} \quad (2.1)$$

Inductance of a solenoid

$$L = \frac{\mu N^2 A}{\ell} \quad (2.2)$$

Rolloff rate of an nth order filter (+HP, -LP)

$$m = \pm 20n \text{ dB/decade} \quad (2.3)$$

Corner frequency of HP or LP, first-order filter

$$f_C = \frac{1}{2\pi RC_S} \quad (2.4)$$

Equation (2.4) solved for R

$$R = \frac{1}{2\pi f_C C_S} \quad (2.5)$$

Voltage divider equation

$$V_o = V_{in} \frac{R_B}{R_A + R_B} \quad (2.6)$$

Transfer function (gain) of a voltage divider

$$\frac{V_o}{V_{in}} = \frac{R_B}{R_A + R_B} \quad (2.7)$$

Corner frequency for simple tone control (pot = 0 Ω)

$$f_C = \frac{1}{2\pi(R_o || R_{in})C_1} \quad (2.8)$$



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