Early electronic devices were intended mainly for speech amplification and reproduction. By the 1930s, however, musical program material gained importance, and an extended frequency response became a commercial necessity. This emphasis grew until, in the 1950s and 1960s, the Harmon Kardon Citation audio amplifier claimed frequency response from 1 to 100,000 Hz flat within a decibel or better. Although today, other performance metrics have surpassed frequency response in advertising emphasis—in part because wide, flat frequency response is now easier to obtain with modern circuitry—frequency response remains a very important parameter.

**Human Hearing**

Humans with pristine hearing (mainly the very young) are often described as being able to hear sounds having frequencies between 20 and 20,000 Hz. In fact, the limits of hearing are difficult to determine, for two reasons. At the lowest frequencies, the ear is relatively insensitive, and the level of a 20 Hz sound has to be so high that it approaches the threshold of feeling, so that a person can perceive acoustic vibrations all the way down to about 1 Hz. Just where hearing merges into feeling is a matter of some debate. At the upper end of the hearing range, facial cilia are able to sense vibration up to about 100 kHz. Again, whether this constitutes hearing is open to debate.

So the range of frequencies that an audio amplifier should cover is by no means well-defined. However, some speaker manufacturers do make super-tweeters designed to reproduce frequencies above 20,000 Hz. And if the amplifier is to be used for an electric musical instrument, a more restricted range is justified, since the instrument’s range may not be greater than about 80 to 5,000 Hz.

Just which factors determine the low- and high-frequency limitations of vacuum tube amplifiers? In order to examine these factors, we need to discuss a bit of electric circuit theory. If a voltage source—AC or DC, it doesn’t matter—is connected to a resistance, the resulting current is given by Ohm’s Law: \( I = V/R \). If the voltage source is of the AC variety, and the resistor is replaced by a capacitor or inductor, the current is given by: \( I = V/X \) where \( X \) is the reactance of the capacitor or inductor. Reactance limits current flow by means of temporary energy storage: capacitive reactance \( X_C \) does so via the electric field, and inductive reactance \( X_L \) stores energy in the magnetic field.

The equations for calculating reactance are:

\[
X_L = \frac{2\pi fL}{C}
\]

\[
X_C = \frac{1}{2\pi fC}
\]

\( f \) is frequency in Hz. \( C \) is capacitance in farads.

\[
X_L = 2\pi fL
\]

\( L \) is inductance in henries. If a capacitor and a resistor are connected in parallel, and \( X_C \) is small compared to the resistance of the resistor, the AC voltage drop across the circuit will be less than if the capacitor were not present. Thus a capacitance appearing between a signal conductor and ground will tend to reduce the signal voltage on that conductor. Thus, the higher the frequency, the lower the signal voltage will be in this arrangement. The opposite is true for an inductor in parallel with a resistor: the lower the frequency is, the lower the signal voltage.

In a series RC circuit, a high capacitive reactance (low frequency) decreases AC signal flow in the resistor. The same is true for a series RL circuit, except that high inductive reactance implies a high frequency.

So how do these facts apply to vacuum tube amplifiers?

**Low-Frequency Response**

Figure 2 shows a triode amplifier stage having three capacitors: one for input coupling (to block DC voltages from the control grid), one for output coupling (to block the DC plate voltage from the following stage), and one to bypass the cathode resistor (to prevent AC voltage from causing negative feedback to the cathode, thereby reducing the gain). All three of these capacitors affect the low frequency response. The coupling capacitors do so by dropping part of the signal voltage at low frequencies so that less of it appears at the control grid of the present stage, or the next stage. The cathode bypass capacitor affects...
fects the low-frequency response because at low frequencies it no longer prevents AC voltage from appearing at the cathode, so that negative feedback reduces the low-frequency gain.

The equation for calculating the value of input coupling capacitor to provide a gain that drops by 3 dB at low frequency \( f_L \) is:

\[
C = \frac{1}{2\pi f (R_s + R_i)}
\]

\( R_s \) is the resistance of the signal source and \( R_i \) is the resistance from grid to ground (the 1-M \( \Omega \) resistor in Figure 2.)

If the resistance of the signal source is not known, or is much smaller than \( R_s \), then \( R_s \) can be omitted from the equation. The calculated value for the capacitor will then be larger than necessary, giving a slightly lower low cutoff frequency.

The same equation can be used for the output coupling capacitor, except that in this case, \( R_s \) is the parallel combination of \( r_p \) (the plate resistance of the tube) and \( R_p \), the resistor between the plate and \( B^* \):

\[
R_s = \frac{r_p R_p}{r_p + R_p}
\]

For the low frequency at which stage gain drops by 2 dB, the capacitor value should be multiplied by 1.316. For 1 dB, multiply by 1.96.

The equation for the cathode bypass capacitor is much more complex:

\[
C_k = \sqrt{\frac{0.25 \left( 1 + \left[ \frac{\mu + 1}{R' + R_p} \right]^2 \right)}{0.75 (2\pi f R_p)^2}} - 1
\]

where \( R' \) is the parallel combination of \( R_p \) and \( R_{gs} \), the grid resistor of the following stage (or the load resistance, if there are no more stages in the amplifier):

\[
R' = \frac{R_p R_{gs}}{R_p + R_{gs}}
\]

The above equation for \( C_k \) gives the value of a cathode bypass resistor in farads to achieve a 3-dB drop in stage gain at the frequency \( f \). For 2-dB or 1-dB drops, the correction factors given above can be applied.

For example, a triode having a \( \mu \) of 20, with a 2700-\( \Omega \) cathode resistor, a 100-k\( \Omega \) plate resistor, and the following stage having a 1-M\( \Omega \) grid resistor, would require a 0.63-\( \mu \)F cathode bypass capacitor for response to be flat within 3 dB down to 100 Hz.

The effects of the various capacitors on low-frequency response combine: If the input coupling capacitor causes a 3-dB drop in response at a certain frequency, and the cathode bypass capacitor causes a 3-dB drop at the same frequency, the amplifier’s overall response will be down 6 dB at that frequency. But this combining can easily be taken care of in the design stage. Since the capacitor values are scalable, if you have a multistage amplifier, you just count up the capacitors and multiply the calculated value for each one by the number of capacitors. For example, a three-stage amplifier will probably have one input capacitor, two interstage capacitors, one output capacitor, and three cathode bypass capacitors (i.e., seven capacitors). Thus, you would calculate the necessary capacitor values and multiply each by seven.

Figure 3 shows a triode amplifier with a transformer-coupled output. Although transformer coupling is mainly used in power amplifiers, the same frequency-response issues pertain to small-signal amplifiers. Transformers are used in amplifiers principally to change impedances. If the number of turns in the primary winding is designated as \( N_p \) and the number in the secondary as \( N_s \), then the voltage, current, and impedance transformation ratios are given by:

\[
\frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{I_p}{I_s}
\]

\[
\frac{Z_s}{Z_p} = \left( \frac{N_p}{N_s} \right)^2
\]

If the secondary winding is unirniterminated, the impedance of the primary winding is composed of the winding’s resistance and inductive reactance. For good efficiency, the resistance is usually quite low. However, in order for the transformer to function well, the inductive reactance must be quite high. This is true because when
the secondary winding is terminated, the impedance reflected back to the primary circuit appears in parallel with the primary’s unterminated impedance. If that unterminated impedance is high (due to a high inductive reactance), the unterminated impedance will have very little effect on the impedance appearing across the primary winding, so that the primary impedance will be as given by the equation above. Otherwise, the impedances and voltages will not be as expected. Since inductive reactance is directly proportional to frequency, the bottom line is that a transformer must have a high inductive reactance in order to provide good low-frequency response. Transformer designers take this into account, along with current-handling capability, in determining wire gauge and number of turns for transformers. Thus, high-power output transformers having good low-frequency response must be large, since they require many turns of fairly large-diameter wire. Input transformers handle much less current, so they can use smaller wire, and are not as large. The reason input, output, and interstage transformers are specified in terms of impedance is that the windings’ inductances must be coordinated with the expected termination impedances in order to achieve good frequency response. Thus, a speaker line transformer having a primary:secondary impedance ratio of 49 Ω:8 Ω would not perform well as a line-level output transformer intended to provide a 490-kΩ load to a triode to feed an 80-kΩ device, even though the impedance ratios are the same.

**HIGH FREQUENCIES**

The high-frequency response limitation of a capacitor-coupled vacuum tube amplifier is mainly caused by the “parasitic” capacitances between the tube’s electrodes. Any time there are two conductors separated by an insulator, you have a capacitor. Thus, in a triode, there is a capacitance between grid and cathode, and between grid and plate. The cathode-to-plate capacitance is generally unimportant. The grid-to-plate capacitance is the important one, because it provides a path for AC signals to travel from the plate back to the grid. Since the signal at the plate is out of phase with the signal at the grid, the result is negative feedback, which reduces the gain. And since the reactance of the grid-to-plate capacitance decreases as frequency increases, the gain is decreased more at high frequencies.

The grid-to-plate capacitance of a 12AX7 is about 1.7 pF, providing a reactance of about 4.7 MΩ at 20 kHz. This is a large enough reactance that it does not cause significant gain reduction. In general, audio amplifiers are not very susceptible to high-frequency response issues from interelectrode capacitances, although this can become an issue at radio frequencies.

Transformers are the other source of high-frequency limitation in tube amplifiers. There is a small capacitance between each pair of adjacent turns in the windings of any transformer, and unless a conductive electrostatic shield is used between the primary and secondary windings, there is a capacitance between the primary and secondary windings as well. These capacitances essentially shunt signal current so that it does not flow as intended in the transformer windings, and thus reduce the gain at high frequencies, where the capacitive reactance is low. Thus, a transformer-coupled tube amplifier (or a transformer-coupled solid state amplifier, for that matter) requires a high-quality transformer in order to have good high-frequency response.