1-1 General Considerations

Audio circuit design is primarily concerned with the planning and detailing of configurations and networks to meet particular performance specifications within the framework of reproducible design in large-scale production. Since uncompromising design techniques are generally unacceptable from the viewpoint of production costs, the audio circuit designer is confronted with the responsibility for making judicious choices of evils; that is, he is forced to accept various calculated risks. Throughout the design procedure, all component and device tolerances and ratings are evaluated within the context of maximum production yield. Yield is defined as the ratio of the number of usable articles at the end of a manufacturing process to the number of articles initially submitted for processing. If an article does not meet performance specifications in production test procedures, it is rejected. Basic specifications for a simple audio amplifier are exemplified in Table 1-1. Design phases are listed in Table 1-2.

Table 1-1. Basic Specifications for a Simple Audio Amplifier

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response</td>
<td>±2 dB, 50–20,000 Hz</td>
</tr>
<tr>
<td>Inputs</td>
<td>Four mikes (hi-Z, 150 kΩ; lo-Z, 200 Ω); two aux., 250 kΩ.</td>
</tr>
<tr>
<td>Temperature range</td>
<td>−20° to +70°C</td>
</tr>
<tr>
<td>Output</td>
<td>6 V at 2%, 4 V at 1%, 2 V at 0.5%</td>
</tr>
<tr>
<td>Gain</td>
<td>mike (hi-Z, 60 dB), 4 mV at 4 V; (low-Z, 80 dB), 0.4 mV at 4 V output.</td>
</tr>
<tr>
<td>Hum/noise</td>
<td>−68 dB below 5 V</td>
</tr>
<tr>
<td>Output impedance</td>
<td>2,000 Ω</td>
</tr>
<tr>
<td>For 117 Vac: Power consumption</td>
<td>1.2 W</td>
</tr>
</tbody>
</table>
Table 1-2. Typical Audio Design Phases

<table>
<thead>
<tr>
<th>Design project is initiated by the sales department</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detailed performance specifications drawn up by engineering department</td>
</tr>
<tr>
<td>Production timetable is scheduled</td>
</tr>
<tr>
<td>Project costs are estimated by accounting department</td>
</tr>
<tr>
<td>Circuitry is drawn up by design engineering department</td>
</tr>
<tr>
<td>Cabinetry is designed by product engineering group</td>
</tr>
<tr>
<td>Mechanical engineering department is alerted</td>
</tr>
<tr>
<td>Circuitry is breadboarded and tested by design engineering department</td>
</tr>
<tr>
<td>Prototype model is constructed by engineering assistants</td>
</tr>
<tr>
<td>Parts list is prepared by design engineering department</td>
</tr>
<tr>
<td>Working drawings are finalized by the drafting department</td>
</tr>
<tr>
<td>Components, devices, and hardware are procured by the purchasing department</td>
</tr>
<tr>
<td>Prototype goes into production</td>
</tr>
<tr>
<td>Merchandising campaign is developed by the advertising and sales groups</td>
</tr>
</tbody>
</table>

(a)

Figure 1-1. Basic amplifier components and devices: (a) symbolic arrangement; (b) appearance of a simple audio amplifier. (Courtesy, Star)

The keystone of audio circuit design procedure is worst-case analysis of the prototype model. This is a basic design technique wherein circuit performance is determined for the case in which all components and devices (Fig. 1-1) have simultaneously assumed their most unfavorable tolerance values, in which the supply voltage is minimum, and in which environmental conditions (temperature, for example) are most adverse. A prototype model is a working model, usually hand assembled, that is suitable for complete evaluation of mechanical and electrical form, design, and
performance. Approved parts are employed throughout so that it will be completely representative of the final, mass-produced equipment. A simplified representation of worst-case analysis is shown in Fig. 1-2. In the case of a complex audio network, it is sometimes difficult to calculate the particular combination of positive and negative tolerances that will produce the maximum detrimental changes in the output.

A tolerance is a permissible deviation from a specified (bogie) value. In other words, a bogie value is a design-center value. Thus resistors may be rated for a tolerance of ±20 percent, or ±10 percent, or ±1 percent. Close-tolerance (tight-tolerance) resistors are more expensive than those with relaxed tolerances. Semiconductor devices ordinarily have wide tolerances; however, the circuit designer may specify tight-tolerance devices. He may specify matched pairs of devices; in this case, a given pair of devices will have closely similar characteristics, although their bogie value will not be the same as that of another given pair of devices. Matched pairs of devices are used in push–pull audio output stages, for example. Note that resistive tolerances may be of little concern in one type of circuit, but of great importance in another. These considerations can usually be evaluated, or at least approximated, from variational analysis of the design equations.

Most electrical tolerances have a finite life expectancy; in turn, the audio circuit designer also evaluates reliability requirements, and allows a corresponding margin for component and device deterioration. Reliability involves the theory of probability; it is defined as the probability that a device will perform adequately for the length of time intended under the operating environment encountered. Quality-control procedures must often be employed to avoid the hazard of ruinous deviations or faults in production runs. Quality control is defined as the control of variation in workmanship, processes, and materials in order to produce a consistent, uniform product. Incoming inspecting procedures may be established in various situations to ensure that components, devices, and hardware are within specified tolerances before they go into production.

### 1-2 Tolerance Requirements and Calculations

Components and devices have exact values and ideal characteristics only in theory. In practice, every fabricated unit is subject to tolerances. For example, a composition resistor may have a rated resistance value of 10,000 ohms (Ω), with a tolerance of ±10 percent. This tolerance rating denotes that the actual value of a resistor chosen at random in a production lot could range in value from 9,000 to 11,000 Ω. Consider the significance of this tolerance on the 266-kilohm (kΩ) bias resistor in Fig. 1-3. The emitter–base junction is biased at 0.2 volt (V) and 33 microamperes (μA). Since the base–emitter voltage (0.2 V) is approximately 2 percent of the bias-resistor voltage (8.8 V), the following conclusions can be drawn in a first analysis:

1. The bias current is determined chiefly by the value of the bias resistor.
2. If the bias resistor has a tolerance of ±10 percent, the resulting tolerance on the bias current will be virtually ±10 percent.
3. If the base–emitter junction resistance has a tolerance of ±10 percent, the resulting tolerance on the bias current will be practically zero.

In other words, the bias current in this configuration is obtained from an approximate constant-current (current) source. Note that an ideal constant-current source would have to employ a bias resistor with infinite resistance. The basic distinction between a constant-voltage (voltage)
source and a constant-current (current) source is depicted in Fig. 1-4. In a constant-voltage arrangement, the load voltage is practically independent of the load-resistance value. On the other hand, in a constant-current arrangement, the load current is practically independent of the load-resistance value. Thus, tolerance considerations in circuits with voltage sources are not the same as in circuits with current sources.

Resistors with equal tolerance values combine in configurations that have the same tolerance value on their net or total resistance, as exemplified in Fig. 1-5. Thus, in Fig. 1-5a, the net resistance of a series combination of 20 percent resistors has a tolerance of 20 percent. Next, in Fig. 1-5b, the net resistance of a parallel combination of 20 percent resistors has a tolerance of 20 percent. It follows that the net resistance of a series-parallel combination of 20 percent resistors, such as depicted in Fig. 1-5c, will have a tolerance of 20 percent. In generalized form, shown in Fig. 1-5d, the net resistance of a resistive T section with a load resistor \( R_{L0} \) in which each resistor has a 10 percent tolerance, will have a tolerance of 10 percent.

Inasmuch as any resistive configuration whatsoever can be reduced to an equivalent T section (insofar as input-output relations are concerned), it is evident that resistors with the same tolerance value will combine in any conceivable network to present a net resistance that has the same tolerance as that of its component resistors.

Observe that, if the resistors in a series or parallel configuration have unequal tolerances, their net resistance will have a tolerance value that is intermediate to the extreme tolerance limits of the component resistors. As an illustration, if a 10-k\( \Omega \) ± 10 percent resistor is connected in series with a 10-k\( \Omega \) ± 20 percent resistor, their net resistance will have a value
on the large-value resistor. As a rough rule of thumb, note that the resistor that has 0.1 the value of the other resistor affects the net tolerance by only 10 percent. Thus the tolerance on the small-value resistor can be substantially relaxed without greatly affecting the tolerance on the net value.

It is possible for positive and negative tolerances to exactly cancel each other. For example, if a 1,000-Ω resistor happens to be at its upper tolerance limit of 1,100 Ω, and it is connected in series with a 1,000-Ω resistor that happens to be at its lower tolerance limit of 900 Ω, their net resistance will have the bogie value of 2,000 Ω. The probability that positive and negative tolerances will cancel each other is theoretically the same as that both resistors will happen to be at their high tolerance limit, or that both will happen to be at their low tolerance limit. Whether the worst-case condition is represented by the high limit or by the low limit depends upon the intended circuit function.

Basic RC Circuit Tolerances

RC circuits are widely used in audio configurations. Capacitive tolerances combine in the same manner as resistive tolerances. However, a different situation is encountered in the combination of resistive tolerances with capacitive tolerances, as exemplified in Fig. 1-6a. In this example, the bogie time constant of the RC circuit is 1 second (s). If the capacitor has a tolerance of ±10 percent, and the resistor has a tolerance of ±10 percent, the time constant of the circuit will have a tolerance of +21 percent and −19 percent. Because the resistance value is multiplied by the capacitance value, the resulting tolerance on the time constant is greater than the tolerance on the individual components. It is also for this reason that the time-constant value has a positive tolerance that is greater than its negative tolerance.

The effect of tolerances on the impedance of an RC circuit is depicted in Fig. 1-6b. If the resistance and the capacitive reactance have equal values, for example, a ±10 percent tolerance on these values causes the circuit impedance to have a ±14 percent tolerance. If a ±10 percent tolerance is assigned to the capacitance value (instead of the capacitive-reactance value), the resulting tolerance on the circuit impedance becomes slightly greater, owing to the inverse relationship between capacitance and capacitive-reactance values. A related basic consideration is the effect of tolerances on the phase angle of an RC circuit. As exemplified in Fig. 1-7, a tolerance of ±10 percent on the R and C values results in a tolerance of ±5 percent on the phase angle of the series RC circuit.

Consider next the effect of tolerances on the frequency response of an RC-coupled stage, such as shown in Fig. 1-8. Since the FET has a very high input impedance, the frequency response of the input circuit is de-
Figure 1-6. Effect of ±10 percent RC tolerances on time constant and impedance: (a) example of time-constant tolerance; (b) example of impedance tolerance.

determined by the values of C and R. Bogie values in this example are 0.1 microfarad (μF) and 47 kΩ. These values provide a −3-decibel (dB) low-frequency cutoff point at point 2 in Fig. 1-9. If the capacitor and the resistor have ±20 percent tolerances, and both have their low-tolerance limiting values, the −3-dB cutoff point occurs at point 3. On the other hand, if the capacitor and resistor both have their high-tolerance limiting values, the −3-dB cutoff point occurs at point 1. From the viewpoint of the audio-amplifier designer, point 3 represents the worst-case situation. Note that the time constant of the emitter return circuit is greater than that

Figure 1-7. Tolerances on RC phase angle.

Figure 1-8. RC-coupled FET stage.

of the gate input circuit in this example. Accordingly, the low-frequency response of the stage is determined by the R and C values in the gate circuit, for all practical purposes.
The audio circuit designer ordinarily assumes that all the resistors in a production lot are within their rated tolerances. This assumption is valid to a very high degree, as all the resistors in the production lot will be found within rated tolerance after subjecting the leads to the extended aging. On the other hand, it is not necessarily true that all the leads in the circuit board, and the leads that have been clipped, bent, torched, and soldered, are within their rated tolerances. This assumption is valid to a very high degree, as all the leads in the circuit board will be found within rated tolerance after subjecting the boards to the extended aging. On the other hand, it is not necessarily true that all the leads in the circuit board, and the leads that have been clipped, bent, torched, and soldered, are within their rated tolerances. This assumption is valid to a very high degree, as all the leads in the circuit board will be found within rated tolerance after subjecting the boards to the extended aging. On the other hand, it is not necessarily true that all the leads in the circuit board, and the leads that have been clipped, bent, torched, and soldered, are within their rated tolerances.
1-3 Basic Device Tolerances

Device tolerances generally differ from component tolerances in that the former are seldom stated as a percentage “spread.” Instead, a bipolar transistor, for example, is ordinarily rated for minimum current gain (beta), maximum collector cutoff current, maximum emitter cutoff current, minimum alpha cutoff frequency, and maximum output capacitance. Thus the audio circuit designer is justified in assuming that all transistors in a production lot will perform at least as well as rated, although an occasional transistor might have twice as much current gain as rated, for example. Low-level transistors are generally rated for maximum noise figure, such as 6 dB. The noise figure is defined as the ratio of the total noise power at the output of the transistor to that portion of the total output noise power attributable to the thermal agitation in the resistance of the signal source (typically 1,000 Ω).

Field-effect transistors (Fig. 1-12) are generally rated for minimum

![Diagram](image)

**Figure 1-12.** Typical characteristics for unipolar transistor amplifier configurations: (a) common source; (b) common gate.

Voltage gain = 50 times
Transconductance: 5000 μhos
Power gain: 17 dB (50 times)
Input resistance: Very high
Output resistance: 20 kΩ
(For generator internal resistance of 500 Ω)

Voltage gain: 1.8
Input resistance: 240 Ω
Output resistance: High
(For generator internal resistance of 500 Ω)

(Continued) (c) common drain; (d) N-channel JFET (depletion); (e) N-channel MOSFET (depletion); (f) P-channel JFET (depletion); (g) P-channel MOSFET (depletion); (h) N-channel MOSFET (enhancement); (i) P-channel MOSFET (enhancement).
power gain, such as 15 dB, and for typical power gain, such as 17 dB. Similarly, FET's are rated for a maximum noise figure, such as 6 dB, and for a typical noise figure, such as 4 dB. Because an FET is a voltage-operated device, a transconductance rating is usually assigned; for example, an FET may be rated for a minimum transconductance of 3,000 microsiemens (μS), and a typical transconductance of 6,000 μS. Note in passing that, although the operating characteristics of both bipolar and unipolar transistors have rather wide tolerances in production lots, the circuit designer can effectively tighten the device tolerances by use of negative feedback. As detailed subsequently, if a large amount of negative feedback is employed in an amplifier circuit, the input-output relations change but slightly as device characteristics are varied over a wide range (see Fig. 1-13).

Integrated circuits, as exemplified in Fig. 1-14, are generally rated for minimum and typical open-loop gain. Open-loop gain is defined as the ratio of the (loaded) output of the amplifier without any feedback to its net input at any frequency; voltage gain is usually stated. For example, an integrated circuit utilized in the configuration of Fig. 1-14 is rated for a minimum open-loop gain of 53 dB and a typical open-loop gain of 58 dB. An integrated circuit is also rated for open-loop —3-dB bandwidth; in this example, the IC is rated for a minimum value of 250 kilohertz (kHz) and a typical value of 300 kHz. This IC is rated for a maximum noise figure of 2 dB at 1 kHz. It is also rated for a minimum output voltage swing of 2 V at 1 kHz, with a total harmonic distortion of 5 percent or less. Its typical output-voltage swing at 5 percent distortion is rated at 2.4 V. The audio circuit designer employs negative feedback to reduce harmonic distortion as much as may be desired.

1-4 Principles of Power Dissipation

A resistor is always rated for maximum power dissipation at room temperature. Most resistors are also rated for maximum voltage drop. As an illustration, if a 1-megohm (MΩ) resistor has 1-watt (W) construction and a 600-V maximum rating, it cannot dissipate more than 0.36 W without exceeding its voltage rating. If its voltage rating is exceeded, the resistor is likely to be short-lived and to arc fail. Whenever a resistor is operated at an elevated ambient temperature, it should be derated accordingly; if it is operated at a reduced ambient temperature, it may be operated at a power level that exceeds its nominal dissipation rating. A derating diagram for a metal-film resistor is exemplified in Fig. 1-15. The circuit designer selects a value of ambient temperature along the horizontal axis

Figure 1-13. Negative-feedback action: (a) plan of a negative-feedback system; (b) improvement of frequency response by 20 dB of negative feedback.
and erects a perpendicular line to the "hypotenuse" in the diagram. This point of intersection is projected to the ordinate, which is calibrated in percentage units. Thus, if the projection occurs at the 50 percent point on the ordinate, the circuit designer will derate the resistor to one half of its rated power dissipation. On the other hand, if the projection occurs at the 155 percent point on the ordinate, he will assign a value of 155 percent to the rated power dissipation of the resistor.

If resistors are connected in series, the permissible voltage drop of the combination is increased, and the permissible power dissipation of the combination is also increased. For example, if two 100,000-Ω 1-W resistors are connected in series, the maximum power dissipation of the combination becomes 2 W. Similarly, if each resistor has a 300-V maximum rating, the series combination will have a 600-V maximum capability. On the other hand, if a 150,000-Ω 1-W resistor is connected in series with a 50,000-Ω 1-W resistor, the power-dissipation capability of the combination is not 2 W. Since both resistors carry the same current, the power dissipated by the 150,000-Ω resistor is three times the power that is dissipated by the 50,000-Ω resistor. Or the maximum power capability of this series combination is 1.33 W. The series-connected resistors operate as a voltage divider, and the voltage drops across the individual resistors

Figure 1-15. Typical derating diagram for a metal-film resistor.
are proportional to their resistance values. In other words, the 150,000-Ω resistor drops 75 percent of the applied voltage, and the 50,000-Ω resistor drops 25 percent of the applied voltage.

When resistors are connected in parallel, the permissible voltage drop for the combination is the same as that of the resistor with the lowest voltage rating. On the other hand, the permissible power dissipation of the combination is greater than that of any individual resistor. As an illustration, if two 50-Ω 5-W resistors are connected in parallel, their 25-Ω combination has a power-dissipation capability of 10 W. However, if a 30-Ω 5-W resistor is connected in parallel with a 150-Ω 5-W resistor, this parallel combination does not have a power-dissipation capability of 10 W. Inasmuch as both resistors have the same voltage drop, the 30-Ω resistor dissipates five times as much power as the 150-Ω resistor; thus the maximum power capability of this parallel combination is only 6 W.

A potentiometer is rated for maximum power dissipation, such as 1 W. This rating applies to the total resistance element. For example, if a 1-W potentiometer has a total resistance of 2,500 Ω, the circuit designer may apply 50 V across the 2,500-Ω element. On the other hand, if the potentiometer is set to its 500-Ω position, it can dissipate only 0.2 W, and a maximum of 10 V can be safely applied across the 500-Ω section of the potentiometer. Consider next the circuit shown in Fig. 1-16. In this example, the potentiometer operates into a comparatively low resistance load. If the potentiometer is rated for a maximum power dissipation of 0.25 W, this rating will be exceeded at any position other than the minimum setting. For example, if the potentiometer is set to its midpoint, the upper half of the resistance element must dissipate practically 0.5 W. Therefore, the potentiometer must be chosen with a suitable power-dissipation rating.

Audio potentiometers are available with various tapers, as shown in Fig. 1-17. Circuit designers employ nonlinear tapers in nonlinear configurations. That is, a potentiometer taper is chosen that is approximately the inverse of the configuration taper. As a result, the net control action is approximately proportional to the number of degrees of potentiometer rotation. This relation makes the setting of the control less critical, and provides a more logical equipment response from the viewpoint of the user. Note that circuits comprising resistance, capacitance, and inductance are basically linear. On the other hand, circuits that include solid-state devices may have nonlinear input-output relationships. For example, a transfer characteristic (base voltage versus collector current) for a small-signal transistor is shown in Fig. 1-18. Another factor that bears on taper

![Figure 1-16. Potentiometer circuit with a comparatively low resistance load.](image)

![Figure 1-17. Standard potentiometer tapers for audio circuitry.](image)
1-5 Law of Probability

Various audio circuit design considerations are based on laws of probability. To cite a very simple example, suppose that there are eight high-value resistors and two low-value resistors in a lot. If a resistor is selected
at random, the assembler is four times more likely to pick up a high-value resistor than to pick up a low-value resistor. Otherwise stated, the probability that he will pick up a high-value resistor is \( \frac{9}{10} \), or \( \frac{9}{5} \). Or the odds are 4 to 1 that the resistor will have a high value. The law of normal distribution defines the range of probabilities for a random occurrence. For example, an extreme worst-case occurrence in a production operation is a random occurrence that has a certain probability. That is, it is not highly probable that all component and device tolerances will happen to have their worst-case values in a random unit of equipment. Nevertheless, this possibility exists, and it is sometimes feasible to calculate the probability of a worst-case occurrence in a production process.

The audio circuit designer may attempt to specify component and device tolerances which ensure that an occasional worst-case occurrence will still fall within acceptable performance limits. More commonly, the designer chooses to relax component and device tolerances from an economical viewpoint, and to take a calculated risk that the number of production rejects will not increase overall manufacturing costs objectionably. A standard probability curve is shown in Fig. 1-20. This example indicates in a qualitative manner how the probability of a worst-case occurrence varies versus the number of units produced. In other words, if an unlimited (theoretically infinite) number of units are produced, there is a 100 percent probability of a worst-case occurrence. Conversely, if very few units are produced, the probability of a worst-case occurrence is very small. This is an elementary statement of a one-tailed process wherein only one half of the total probability curve is applicable. If we consider the distribution of high- and low-value resistors in a random production lot, for example, a two-tailed analysis is employed wherein the total probability curve applies.

Worst-case occurrences in a production operation can be analyzed in terms of standard probability calculations only when the component and device tolerances are truly random. It often happens, in practical situations, that tolerances in a parts shipment tend to cluster toward the low end or toward the high end of the specified limits. Although clustering can be taken into account in the probability calculations, at least in a general way, design engineers seldom take this complication into account, and assume that component and device tolerances are truly random. Technically, the probability distribution is a mathematical model that shows a representation of the probabilities for all possible values of a given random variable. The probability of success is defined as the likelihood that a production unit will function satisfactorily for a stated period of time when subjected to a specified environment.

### 1-6 Audio Design Pitfalls

Experienced circuit designers know that unexpected pitfalls may be encountered in various phases of a design project. For example, unless amplifiers are adequately decoupled, they may become unstable when connected to a common power supply. Instability may impair the system frequency response and cause distortion; in severe cases, motorboating (self-oscillation) can occur. A typical power-supply configuration for an audio system is shown in Fig. 1-21. Although the internal impedance of the power supply is small, it is not zero. As the filter capacitors C1, C2, and C3 gradually deteriorate, the internal impedance of the power supply increases. Note also that there is a small value of common impedance between outputs 1 and 2. Because of these residual power-supply impedances, an amplifier that operates satisfactorily from a bench power
at random, the assembler is four times more likely to pick up a high-value resistor than to pick up a low-value resistor. Otherwise stated, the probability that he will pick up a high-value resistor is \( \frac{4}{10} \), or 0.4. Or the odds are 4 to 1 that the resistor will have a high value. The law of normal distribution defines the range of probabilities for a random occurrence. For example, an extreme worst-case occurrence in a production operation is a random occurrence that has a certain probability. That is, it is not highly probable that all component and device tolerances will happen to have their worst-case values in a random unit of equipment. Nevertheless, this possibility exists, and it is sometimes feasible to calculate the probability of a worst-case occurrence in a production process.

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Overview of Basic Design Principles

Figure 1-22. Frequency characteristics of a typical 8-μF electrolytic capacitor.

Figure 1-23. Example of feedback path in a common power-supply system.

1-7 Underwriters' Laboratories (UL) Approval

Supply may or may not remain stable when it is energized from a common power supply that also energizes other amplifiers in a system. The impedance of a typical 8-μF electrolytic capacitor is exemplified in Fig. 1-22. Therefore, the audio-circuit designer should be aware of this pitfall, and he should check any new amplifier arrangement under system conditions before it is released to production.

An example of a feedback path in a common power-supply system is shown in Fig. 1-23. A phase reversal occurs from base to collector of Q2, and another phase reversal occurs from base to collector of Q3. In turn, the common power-supply impedance Z2 feeds back in-phase energy from the collector of Q3 to the base of Q1. This is a regenerative condition that causes a peaked frequency response. This distortion occurs at the frequency for which the system within the feedback loop has maximum gain. If the value of Z2 exceeds a certain critical value, Q2 and Q3 with motorboar, and a pput-putt sound will be radiated from the speaker. Next, observe that emitter resistors R6 and R10 are effectively decoupled from the power-supply impedance by capacitors C4 and C7. Therefore, impedance Z1 can have a high value without development of a significant feedback path. To stabilize the collector-return circuits, the circuit designer includes an RC decoupling “network” in each collector-return lead. This “network” comprises a series resistor and a shunt capacitor.

If a prototype model operates within performance specifications, the designer may tend to relax vigilance and to assume that the circuit has been adequately verified. However, the careful designer will analyze the model for possible pitfalls that may have been overlooked. For example, all electronic equipment generates more or less heat. Heat sources are localized within a unit of equipment. The rise of internal operating temperature above ambient is difficult to calculate and must usually be determined experimentally. A critical designer checks equipment operation over an extended period in the highest specified ambient temperature. He measures the temperature at each component and device that is rated for a maximum operating temperature. If any measurement reveals that there is little or no margin between the rated maximum and the operating temperature (under worst-case conditions), the designer will modify the parts list and use a suitably derated component or device.

1-7 Underwriters' Laboratories (UL) Approval

Specific guidelines have been established by the Underwriters' Laboratories for minimizing shock and fire hazards in the design of electrical and electronic equipment. The Underwriters' Laboratories are a branch of the National Board of Fire Underwriters. A consumer electronics product
that has been examined by the UL, and which has been accepted, is permitted to carry a tag or label of approval, as shown in Fig. 1-24. Circuit designers can obtain a pamphlet from any UL office to determine the prevailing electrical and mechanical requirements for approval by UL inspectors. Specific approval of each design and model is necessary. Many municipalities require UL approval for all products sold in their jurisdictional areas.

Figure 1-24. Typical Underwriters’ Laboratories labels.

Some basic UL requirements are as follows. A power transformer used in a consumer-electronics product must be completely enclosed in a metal or other noncombustible housing to prevent the escape of flames or molten metal in case the transformer were destroyed by a catastrophic overload. A power transformer with a UL-approved housing is depicted in Fig. 1-25. A circuit breaker or fuse must be included in the input line of the power supply to minimize the danger of fire in the event of a serious overcurrent demand anywhere in the equipment circuitry. Temperature limits for various classes of materials must be observed. Each conductor is required to have adequate cross section and insulation for its intended current flow, operating temperature, and application. Power cords must meet specific requirements for stranded conductors at the rated current demand, and must be adequately insulated. A power cord must be provided with strain relief inside the equipment; the cord must enter through an insulating bushing that will prevent cutting or fraying of the insulation on the cord. Also, the power cord must be secured at its entry point so that it cannot be pushed back into the interior of the cabinet.

1-8 Black-Box Concept

The audio-circuit designer often starts with a black-box concept, defined by performance specifications. This is a useful mathematical approach to an electronic configuration that concerns itself only with input and output parameters and relations, and ignores the interior elements, discrete or integrated. A black-box representation for a high-fidelity preamplifier is pictured in Fig. 1-26. The input and output data are basic design requirements. Next the audio circuit designer proceeds to break down the black box and to implement the basic performance specifications. For example, he will determine how many stages are required and decide on the types of devices that will be utilized. Then circuit details are worked out, and the design is breadboarded. If the breadboard model meets the black-box data, it is next constructed in a prototype model form. Further tests are then made to ensure that the design is reproducible in large-scale production.

Figure 1-26. Example of an audio black-box concept.

1-9 Basic Types of Distortion

Five basic types of distortion include frequency distortion, phase distortion, amplitude distortion, transient distortion, and parasitic distortion, as exemplified in Fig. 1-27. Although there is a relation between frequency
distortion and transient distortion, this relation is complex, and it is advisable for the audio circuit designer to regard them as separate categories. There are various forms of square-wave distortion, as shown in Fig. 1-28. High-fidelity components are usually tested with a square-wave repetition rate of 2 kHz, although other repetition rates may also be utilized. Crossover distortion is depicted in Fig. 1-29. It is essentially a form of amplitude distortion and produces harmonics in the output wave.
form. However, crossover distortion differs from clipping distortion, for example, in that the percentage of crossover distortion measured with a harmonic-distortion meter increases as the amplifier power output decreases. On the other hand, the percentage of clipping distortion increases as the amplifier power output increases.

Crossover distortion is typically produced by class B push–pull amplifiers when the transistors are operated with zero bias. Hence designers generally operate push–pull output stages in class AB, with a small amount of forward bias on the transistors. If excessive forward bias is employed in class AB operation, stretching distortion occurs. When one
1-10 Phon and Mel Units

The phon is a loudness unit. Thus it is distinguished from the decibel referred to 1 milliwatt (dBm), which is a power unit. The loudness unit is of basic importance in audio systems, because the ear is not equally responsive to a given power level at various frequencies. Thus the phon is a function of frequency and represents different power levels at different frequencies; a phon unit has the same loudness at any chosen frequency. The phon relation to frequency and to decibels is depicted in Fig. 1-32. By definition, a frequency of 1 kHz is taken as a common reference point, so that at this frequency the phon level is equal to the decibel level (provided that the same reference level is used for both measurements). Zero reference level for the loudness unit is standardized at 0.0002 dyne/square centimeter (cm²). With reference to Fig. 1-32, a loudness control in a high-fidelity amplifier is frequency compensated to conform to the curves of constant-phon values at corresponding power levels.

The phon unit should not be confused with the *mel* unit. In other words, the phon is a unit of loudness, whereas the mel is a unit of pitch. A pure 1-kHz sine wave, 40 dB above a listener’s threshold, produces a pitch of 1,000 mels as perceived by the listener. The pitch of any sound that is judged by the listener to be $n$ times that of a 1-mel pitch has a value of $n$ mels. Like the phon, the mel is a subjective unit, whereas the decibel is a physical unit. The relation of the mel scale to frequency is shown in Fig. 1-33. Observe that if 1,000 mels is taken as a reference frequency, it corresponds to a frequency of 1,000 hertz (Hz). Next, a pitch of 2,000 mels corresponds unexpectedly to a frequency of 4,000 Hz. Again, 500 mels corresponds unexpectedly to a frequency of 400 Hz. These examples point up the fact that perception of sound is a nonlinear type of response.

1-11 Low-Frequency Boost

When the audio circuit designer desires to obtain extended low-frequency response from an RC-coupled amplifier, a reasonable extension can be obtained by including a low-frequency boost circuit in the first stage of the amplifier, as shown in Fig. 1-34. When suitable values of boost com-
Overview of Basic Design Principles

Components, $R_B$ and $C_B$, are utilized, the low-frequency response can be appreciably improved. In this example, the first screen photo shows the 60-Hz square-wave response of the uncompensated amplifier. Next, 60-Hz square-wave responses for various values of $R_B$ and $C_B$ are illustrated. It is seen that a choice of 15 kΩ and 2 μF provides optimum 60-Hz square-wave response in this example. Note that the required values of $R_B$ and $C_B$ may be rather critical in a multistage arrangement; also, these values depend considerably upon the tolerance deviations of the $R$ and $C$ coupling networks in the various stages.

![Diagram of an electronic circuit](image)

(a) Output

$R_L$

$R_B$

$C_B$

$V_{CC}$

Figure 1-34. Low-frequency boost circuit: (a) $R_B$ and $C_B$ provide low-frequency boost; (b) examples of low-frequency square-wave response for various values of $R_B$ and $C_B$.

1-12 Presence Control

A presence control is employed in some high-fidelity systems to permit the listener to augment the output in the region of 2 kHz, as exemplified in Fig. 1-35. Listeners often prefer this frequency characteristic in comparison with a precisely flat midrange frequency response. A presence control is sometimes provided in the form of a level control for the midrange speaker in a speaker system. Alternatively, an RC filter network may be included in the preamplifier configuration. It is also possible to use a speaker crossover network that provides augmented response in the midrange.

![Graph showing presence control effect](image)

Figure 1-35. Effect of presence control action in a hi-fi system.