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PARALLELING AUDIO AMPLIFIER ICs ALLOWS FOR LOW COST AND HIGH OUTPUT POWER.

Current-sharing IC audio-power amplifiers drive heavier loads

Audio-power amplifier ICs suit low-power applications because of their low cost, parts count, and size. Applications demanding higher output power challenge designs based on IC power amplifiers. The IC's normally appealing size can become a disadvantage when you factor in thermal considerations. The size of the IC concentrates the heat flux on a small area on the heat sink, generating large thermal gradients. These gradients limit the power dissipation of the IC as the case temperature rises and approaches the maximum junction temperature.

SUPPLIES AND SWINGS

Beyond thermal limitations, IC power amplifiers must also operate within electrical bounds. The IC power amplifier's output current is limited by the maximum current density that the internal bond wires and silicon can accommodate. The amplifier requires a minimum operating voltage to keep the distortion levels to a minimum

One method of increasing the power from IC amplifiers that overcomes these problems is connecting amplifiers in parallel so that they share the load current. This arrangement not only relaxes the current requirement on each amplifier, but it also spreads the heat flux on the heat sink by introducing more heat sources, each having a smaller heat flux.

Lowering the speaker's impedance and maximizing the amplifier's output swing increase output power:

$$P_{AVE} = \frac{V_{OUT}^2}{2R_{SP}}, \quad (1)$$

where P_{AVE} is the average output power delivered to the speaker, V_{OUT} is the peak output voltage, and R_{SP} is the nominal speaker impedance.

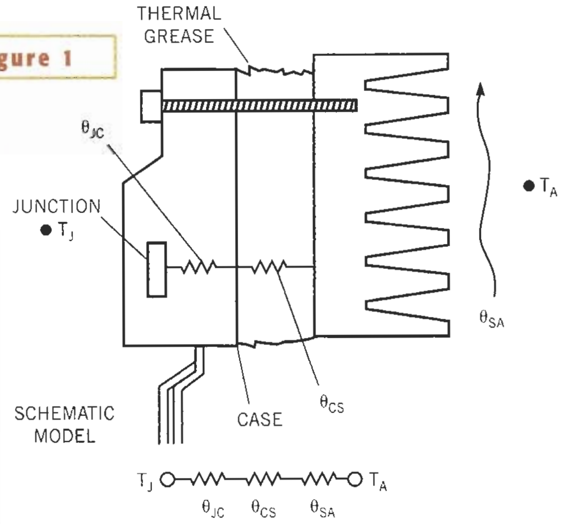
Using Kirchhoff's Voltage Law, the sum of the voltages across the amplifier, V_{AMP}, and the load, V_{OUT}, must equal the supply voltage:

$$V_S = |V_{AMP}| + |V_{OUT}|. \quad (2)$$

Next, the IC amplifier's data sheet usually states what minimum average output power, P_{MIN}, the amplifier will produce with a specified supply voltage, $V_{S(SPEC)}$ and speaker impedance, R_L. Solving **Equation 2** for V_{OUT}, inserting the result into **Equation 1**, and using these specified values, the expression for V_{AMP} gives:

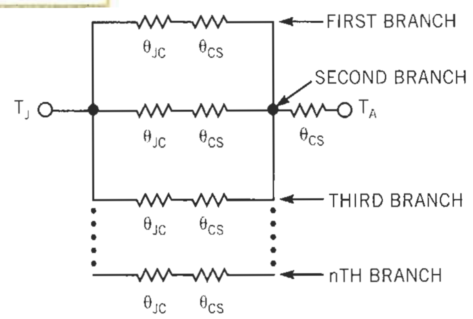
$$V_{AMP} = V_{S(SPEC)} - \sqrt{2P_{MIN}R_L} = V_{HR}(MAX). \quad (3)$$

Figure 1



An amplifier's thermal model accounts for three primary thermal-resistance terms.

Figure 2



Multicell amplifiers create parallel branches in the thermal model, but the heat-sink-to-ambient term remains fixed for a given heat-sink size.

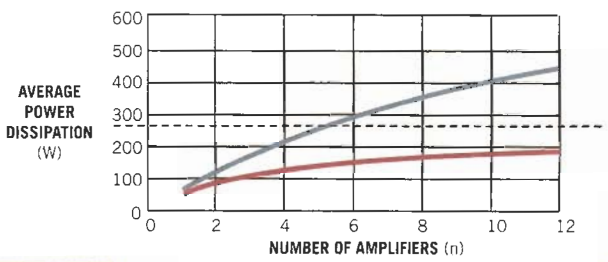


Figure 3

For a fixed heat-sink size, the benefit of additional amplifiers tapers off with increasing numbers of amplifiers.

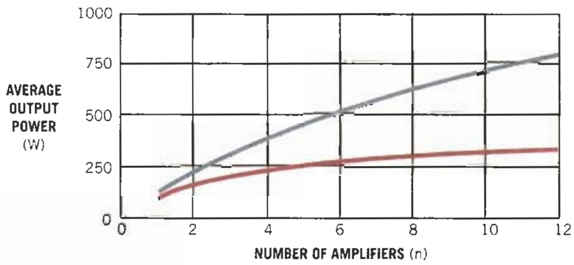


Figure 4

The attainable output power also tapers off with increasing numbers of amplifiers.

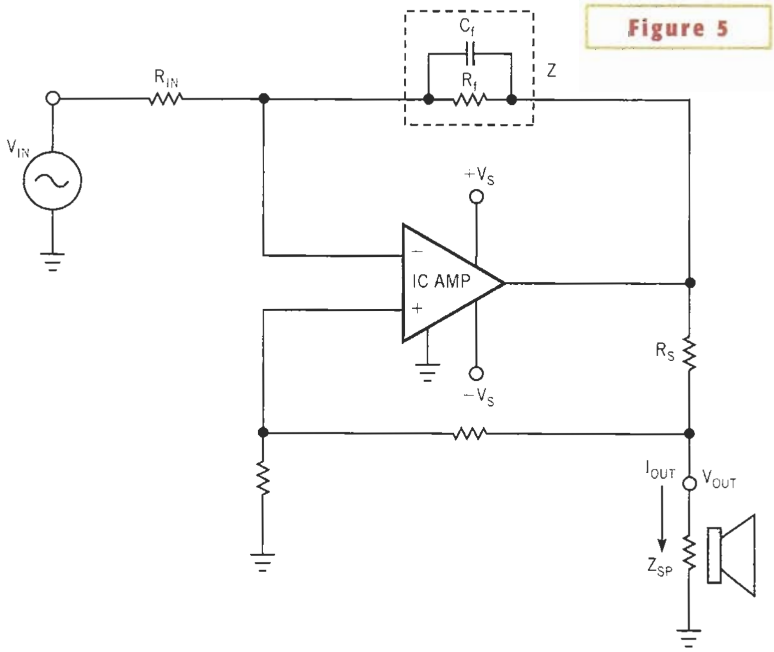


Figure 5

This transconductance amplifier cell forms the basis for a multicell compound amplifier.

Note that the positive root is extraneous, because it gives a value that violates Kirchhoff's Voltage Law. **Equation 3** gives the maximum peak headroom voltage, V_{HR}(MAX), needed to achieve the specifications in the data sheet. This value is useful when considering different power-supply voltages and speaker loads.

THERMAL MANAGEMENT

The average power, P_{AVE}, that the amplifier dissipates is:

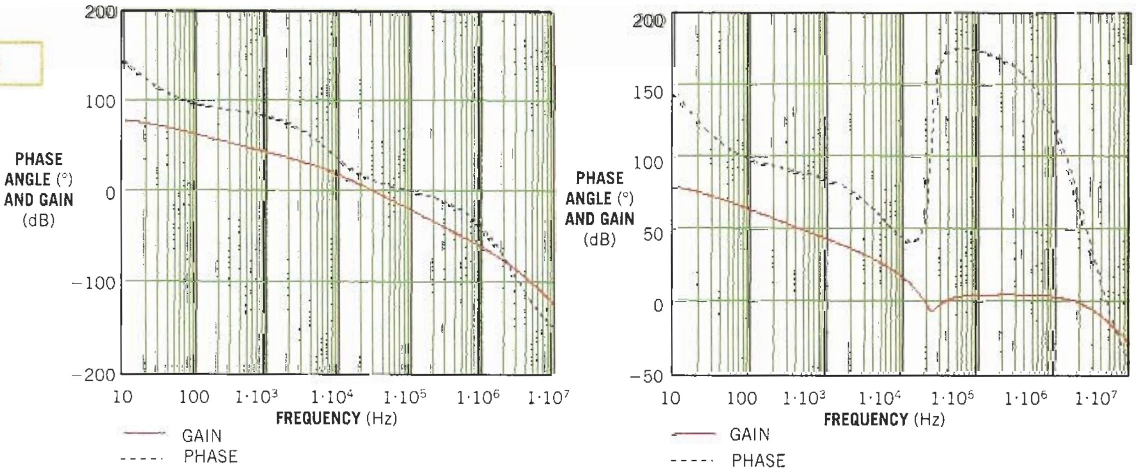
$$P_{AVE}=\frac{V_{OUT}}{2\pi R_{SP}}(4V_S-\pi V_{OUT}). \qquad (4)$$

Note that **Equation 4** is parabolic. P_{AVE} reaches a maximum when $V_{OUT}=2V_S/\pi$, so if the music listener sets the volume to this value, the amplifier will dissipate maximum power. To find this value, substitute $2V_{SUP}/\pi$ for V_{OUT} in **Equation 4**:

$$P_{AVE}(MAX)=2\frac{V_S^2}{\pi^2 R_{SP}}, \qquad (5)$$

where P_{AVE}(MAX) is the maximum aver-

Figure 6



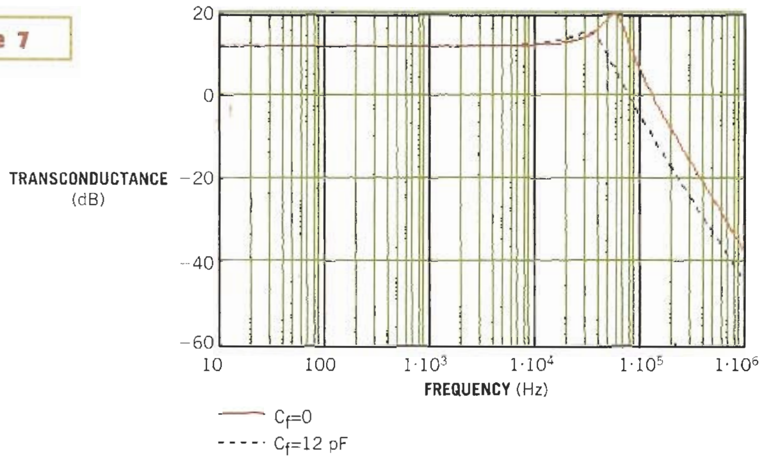
An amplifier cell's phase margin (a) improves by about 30° with the addition of a 12-pF compensation capacitor (b).

age power dissipation of the amplifier. This value is the one to use in the thermal model. **Figure 1** shows a thermal model of a single amplifier and an equivalent schematic. Fourier's Law of Conduction gives the relationship between the power dissipation, P, and the thermal model's variables:

$$P=\frac{T_J-T_A}{\theta_{JC}+\theta_{CS}+\theta_{SA}}, \qquad (6)$$

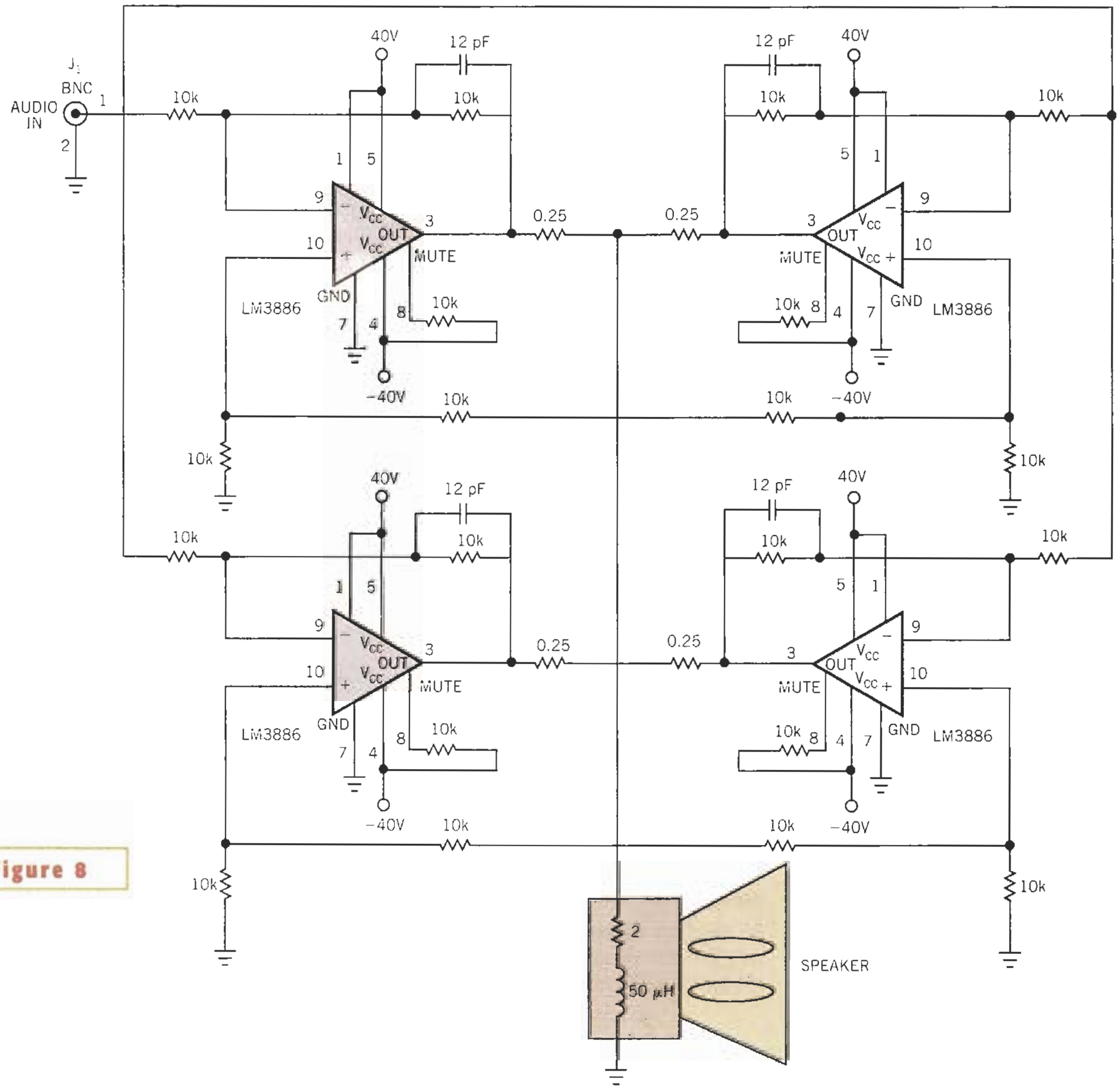
where T_J is the junction temperature in degrees Celsius; T_A is the ambient temperature in degrees Celsius; θ_{JC} is the thermal resistance from junction to case; θ_{CS} is the thermal resistance from case to heat sink; and θ_{CA} is the thermal resistance from the heat sink to ambient.

Figure 7



You can see the compensation capacitor's effect in the amplifier's closed-loop response.

Figure 8



Four current-sharing cells form the complete amplifier.

Attaching multiple amplifiers to the same heat sink provides additional branches for the heat to flow (**Figure 2**). Assuming identical thermal paths for each device, **Equation 7** models the net behavior:

$$P_{AVE}(MAX)=\frac{n(T_J-T_A)}{\theta_{JC}+\theta_{CS}+n\theta_{SA}}. \quad (7)$$

IC amplifiers' data sheets state the maximum allowable junction temperature. As a numerical example, assume that θ_{JC}41°C/W, θ_{CS}40.4°C/W, the maximum allowable junction temperature is 120°C, and the ambient temperature is 20°C. A heat sink, such as a Wakefield Engineering's (www.wakefield.com) 392-180AB, which is 180 cm in length, has a θ_{SA} of 0.43°C/W with natural convection and 0.11°C/W with forced air. As you add amplifiers to the heat sink, the benefit of additional amplifiers decreases (**Figure 3**). The total output power versus n—the number of amplifiers—is also of interest (**Figure 4**). You can find this function by substituting **Equation 6** into **Equation 5** and calculating R_{SP}—the corresponding speaker impedance. Find the final answer by inserting the calculated speaker impedance into **Equation 1** with the maximum output voltage from **Equation 5** to get:

$$P_{AVE}=\frac{n\pi^2\left(V_{S(SPEC)}-V_S-\sqrt{2P_{MIN}R_L}\right)^2}{4V_S^2(\theta_{JC}+\theta_{CS}+n\theta_{SA})}(T_J-T_A) \quad (8)$$

COMBINING AMPLIFIERS

As stated, you could parallel the IC amplifiers together so that they share the output current. One method of combining amplifiers in parallel to share the load current uses the IC amplifier as a transconductance gain cell (**Figure 5**).

The relationship between the input signal, V_{IN}, the output current, I_{OUT}, and the output voltage, V_{OUT} is given by

$$I_{OUT}=\frac{R_O-GZ}{R_OR_S+ZR_S+RR_S+ZR_O+R_OR+GRR_S}V_{IN}+\alpha V_{OUT}, \quad (9)$$

$$\alpha=\frac{1}{2}\bullet\frac{-2R^2-R^2G-2RZ+RZG-RR_S-3R_OR-GRR_S-ZR_S-ZR_O-R_OR_S}{R(GRR_S+RR_S+R_OR+ZR_O+ZR_S+R_OR_S)}; \quad (10)$$

where G is the open loop gain of the amplifier; $R=R_1=R_2=R_3$; Z is the parallel impedance formed by R_f and C; R_O is the amplifier's output resistance; and R_S is the shunt resistance.

You can examine the transconductance amplifier's behavior at both high and low frequencies. At lower frequencies, your implementation should allow you to assume a large open-loop gain, G, and a large capacitor impedance, so that Z is approximately equal to R_f, which is equal to R. If these assumptions hold, **Equation 7** reduces to:

$$I_{OUT}=\frac{-V_{IN}}{R_S}-\frac{V_{OUT}}{2R}. \quad (11)$$

Amplifiers may require a minimum closed-loop gain, $A_O(MIN)$, to ensure stable operation. To obtain the value of $A_O(MIN)$ you must calculate the transconductance amplifier's feedback factor, β. For amplifiers driving speaker impedances of less than 100Ω,

$$\beta=\frac{-1}{2}\bullet\frac{Z_{SP}(R-Z)+2RR_S}{(Z_{SP}+R_S+R_O)(R+Z)}. \quad (12)$$

For inband signals, C_F essentially has no effect, leaving Z equal to R. Therefore, **Equation 12** reduces to:

$$\beta=\frac{-1}{2}\bullet\frac{R_S}{(Z_{SP}+R_S+R_O)}. \quad (13)$$

The inverse of β is the closed-loop gain, so you can use this **equation** to select the shunt resistor, R_S, to satisfy the inequality $1/\beta>A_O(MIN)$ for the range of speaker impedances you expect to drive.

Given normal part-to-part variations and differences in speaker inductance, you should design for additional phase margin. One simple method is to add a capacitor, C_f, across R_f (**Figure 5**). You can examine the feedback factor, β(f), and, more important, the loop gain, T(f), to see what effect C_f has on the phase margin. First, the Z in **Equation 12** becomes the parallel combination of C_f and R_f. Moreover, if you are going to employ multiple transconductance amplifiers, the real component of the speaker impedance, R_{SP}, that each amplifier sees is bigger by a factor of the number of amplifiers used. In other words, if $V_{OUT}=I_{OUT}R_{SP}$ with a single amplifier, then $V_{OUT}=I_{OUT}nR_{SP}$ for n amplifiers. As a result, each amplifier sees a load of $nR_{SP}+j2\pi fL_{SP}$. Substituting these values into **Equation 12** yields:

$$\beta(f)=\frac{-1}{2}\bullet\frac{\left[n(R_{SP}+j2\pi fL_{SP})+2R_S\right]j\pi fC_fR+R_S}{\left[n(R_{SP}+j2\pi fL_{SP})+R_S+R_O\right](j\pi fC_fR+1)}. \quad (14)$$

Calculating the loop-transfer function requires knowledge of the IC amplifier's open-loop-transfer function. For example, the data sheet for National Semiconductor's LM3886 approximates the open-loop transfer function as:

$$G(f)=\frac{6.33\bullet10^{19}}{(2.65\bullet10^6+jf)^2(13.3+jf)}. \quad (15)$$

It has an internally compensated pole around 13 Hz and two poles near 2.65 MHz. Continuing with the example, assume numerical values of: $R_O=0.4\Omega$, $R=10$ kΩ, $R_S=0.25\Omega$, $R_{SP}=2\Omega$, n=4, and $L_{SP}=50$ μH.

The loop-transfer function, $T(f)=\beta(f)G(f)$, expands to:

$$T(f)=\frac{-1}{2}\bullet\frac{\left[4\left(2+j2\pi f\left(50\bullet10^{-6}\right)\right)+2\bullet0.25\right]j\pi fC_f10^4+0.25}{\left[4\left(2+j2\pi f\left(50\bullet10^{-6}\right)\right)+0.25+0.4\right](j\pi fC_f10^4+1)}\bullet\frac{6.33\bullet10^{19}}{(2.65\bullet10^6+jf)^2(13.3+jf)}. \quad (16)$$

Plots of **Equation 16** with the associated phase curves demonstrate the effect of feedback compensation (**Figure 6**). **Figure 7** depicts the closed-loop response.

Finally, the composite amplifier's input impedance, R_{IN}, is:

$$R_{IN}=RR_S\frac{nR_{SP}+2R}{n(2RR_S+nRR_{SP}+nR_SR_{SP})}. \quad (17)$$

Figure 8 shows a complete schematic of a four-cell amplifier.□

AUTHOR'S BIOGRAPHY

Robert LeBoeuf is a staff engineer in National Semiconductor's applications group, where he designs circuitry that employs National Semiconductor's ICs. He holds a master's degree in mathematical physics from the University of Massachusetts—Lowell. His interests include parenting, studying physics, and woodworking.