Heat Dissipation and Power Compression in Loudspeakers*

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In the professional audio market today there is a variety of transducers with high power ratings. As these drivers generally are less than 5% efficient, they convert almost all of their input power to heat. How this heat is dealt with is discussed, and conclusions about power compression effects in a variety of popular designs are revealed.

0 INTRODUCTION

Recently several articles describing heat dissipation and power compression in transducers have been written [1]–[4], yet there is a call for more information regarding these phenomena [5] and a public desire to understand the performance expected from standard professional drivers. Little is actually published by manufacturers about the heat dissipation and power compression capability of their drivers. It is the purpose of this paper to describe typical mechanisms and present performance expected from popular designs. No manufacturers are mentioned, and pot structure topologies are referred to as generic types. From this, the readers can associate the given geometry that is closest to their drivers of choice and derive the level of performance to be expected.

1 FUNDAMENTALS OF HEAT DISSIPATION

Loudspeakers are inefficient devices. Electrical-to-acoustical conversion efficiencies are typically less than 5%. Consequently 95% or more of the power delivered to a loudspeaker is turned into heat, and this heat must be dissipated. The source of the heat is the voice coil, and the heat generated is

$$Q = i^2 Z \qquad (1)$$

where

Q = heat power, W
i = current in voice coil, A
Z = minimum impedance, Ω.

A special note on impedance: The heat dissipated is greater than $i^2 Re$, where Re is the dc resistance. Additional resistance that will generate heat is due to eddy currents in the magnet structure. When considering the heat generated, this is a part of the minimum impedance. The minimum impedance is almost always larger than the expected value obtained by incorporating the acoustical radiation resistance. More specifically, the minimum impedance will be more than 5% greater than the dc resistance for a driver that is 5% efficient. Consequently the minimum impedance is a better value to use when calculating Q.

Because the heat generated is in the center of the loudspeaker, the motor structure and frame are utilized as thermal paths to dissipate the heat from the voice coil. The thermal performance can be represented by a classical analogous lumped-element circuit model comprised of resistors and capacitors, as shown in Fig. 1. The power applied to the circuit can be thought of as Q, and the voltage potential at the voice coil is the temperature of the voice coil. Ambient air temperature is ground. The resistors can be modeled as

$$R = \frac{L}{AK} \qquad (2)$$

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where

R = thermal resistance, °C/W
L = length of path, m
A = cross-sectional area of path, m^2
K = thermal conductivity, °C · m/W.

The capacitors can be modeled as

$$C = MH_s \tag{3}$$

where

C = thermal capacitance, J · K
M = mass, kg
H_s = specific heat, J/kg · K.

Defining the resistor and capacitor elements can be a little difficult, and the ideal situation would be a nearly infinite three-dimensional matrix of thermal paths and capacitances. Finite-element analysis programs are available which can do this very thing. Unfortunately the turbulence and airflow created by the diaphragm will give results that vary from the classical analysis, and which finite-element analysis programs cannot predict.

As complex as this appears to become, the circuit can in fact be simplified. If we choose any loudspeaker, apply a signal to the voice coil, and plot the voice-coil temperature versus time, say by monitoring de resistance, we obtain the characteristic curve in Fig. 2.

This curve suggests a transfer function of a much simpler circuit. The model can be easily represented by two cascaded RC circuits, as shown in Fig. 3. The differential equation governing the transient behavior of a simple RC thermal circuit is

$$Q\,\mathrm{d}T = MH_s\mathrm{d}T + \frac{\Delta T}{R}\,\mathrm{d}T \tag{4}$$

where ΔT is the coil temperature rise above ambient in degrees Celsius. Solving the equation for temperature rise as a function of time yields

$$\Delta T = QR\ 1 - \exp\left(\frac{t}{MH_sR}\right) . \tag{5}$$

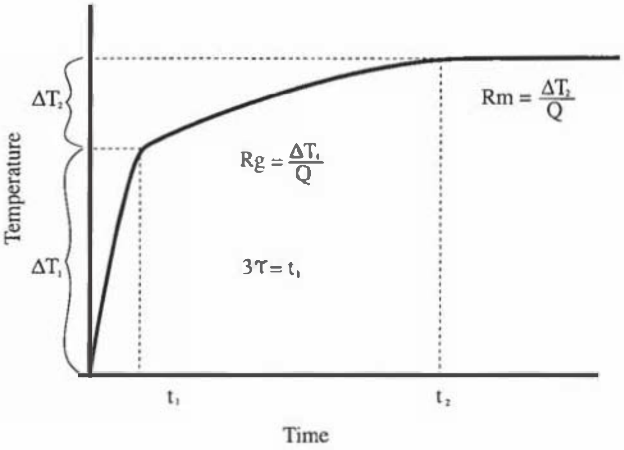


Fig. 2. Characteristic voice-coil temperature versus time.

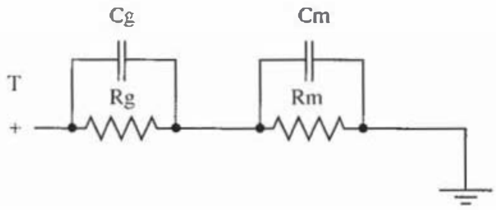


Fig. 3. Two cascaded RC circuits. T—temperature of voice coil; ground—ambient temperature; R_g—thermal resistance of path from coil to magnet structure; C_g—zone thermal capacitance of voice coil and nearby surroundings; R_m—thermal resistance of magnet structure to ambient air; C_m—thermal capacitance of magnet structure.

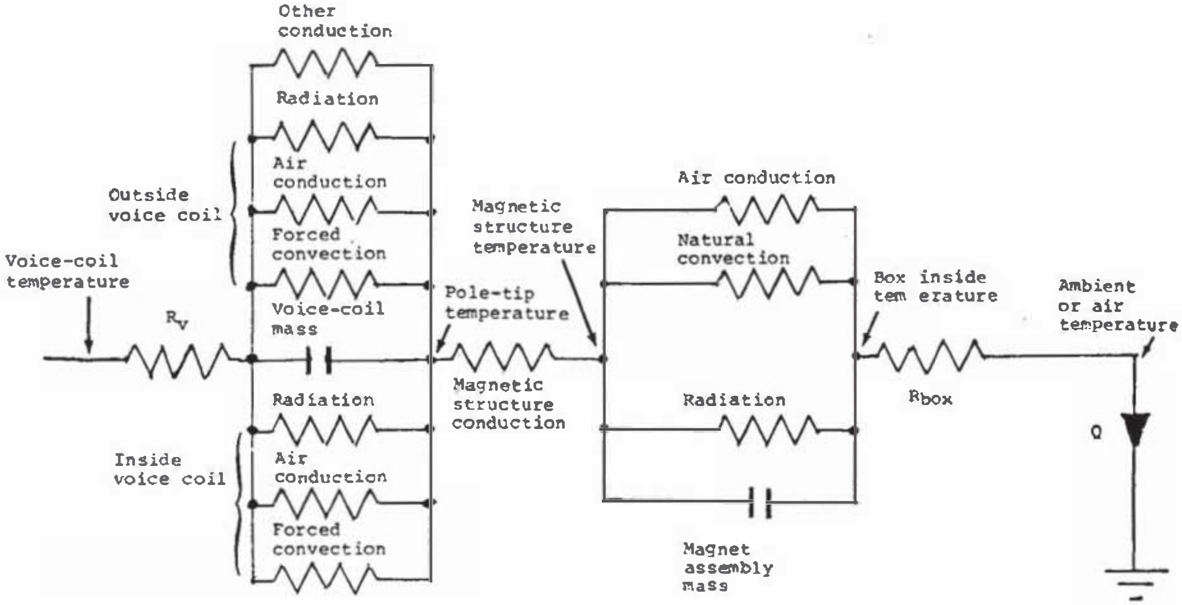


Fig. 1. Circuit model. From Henricksen [1].

The thermal time constant τ, an elapsed time at which the temperature has risen 63% of the way toward its maximum value, is given by

$$\tau = MH_sR \ . \tag{6}$$

At time 3τ the temperature rise would be at 95% of the final value. This final value of temperature rise is of course

$$\Delta T = QR \ . \tag{7}$$

The first period from $t = 0$ to $t = t_1$ and the temperature rise from ambient to ΔT_1 are the response of the first RC pair; the time from t_1 to t_2 and the temperature change from ΔT_1 to ΔT_2 are from the second RC pair. Almost all loudspeakers will generate a curve similar to that in Fig. 2 when a constant voltage source is applied, and each loudspeaker can be characterized by a t_1, t_2 and ΔT_1, ΔT_2 for a given power. The first RC knee is defined by the thermal resistance of the voice coil to its nearby surroundings and by the thermal capacitance of the coil and a small zone around it. The second knee is defined by the thermal resistance of the pot structure and frame to air and by the thermal capacitance of the structure.

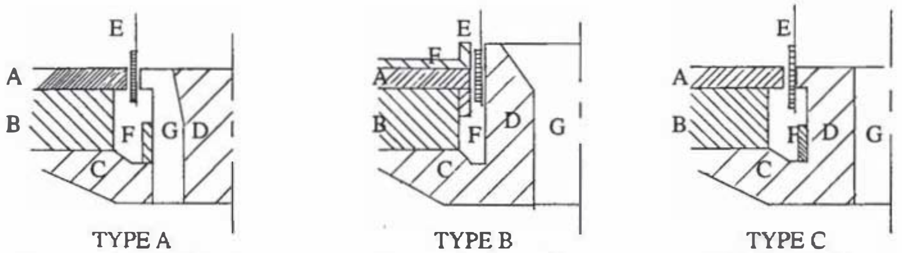
While detailed examinations of the zone resistance and capacitance values can and should be carried out by the loudspeaker designer to understand and attempt to improve overall heat dissipation, the final effective R and C elements, being a combination of several more detailed elements, can be measured and expressed in simple terms. It is, of course, the labor of the loudspeaker designer to minimize thermal resistances and maximize thermal time constants.

In close examination of typical voice-coil heat-up curves such as Fig. 2 it is obvious that the first RC circuit defining the short-term thermal behavior (the voice-coil area) is considerably worse than the second circuit. The thermal capacitance is low and heat-up is very rapid. The thermal resistance, derived from ΔT_1, is much larger than that derived from ΔT_2. What this suggests is that the voice coil is the weak link in dissipating heat.

2 POPULAR DESIGNS

Fig. 4 details several popular voice-coil magnetic gap configurations. The loudspeakers represented range in voice-coil diameter from 2½ to 4 in (64 to 101 mm), and all measurements were made on 15-in drivers (381-mm) drivers. Different philosophies for heat dissipation are used. Two of the more effective methods are the encased gap (type B) and the convection-cooled gap (type A). The former method provides a thermal path for the entire coil by surrounding the voice coil with metal. This works effectively regardless of the input signal (that is, independent of whether or not there is cone motion), but it is unable to take advantage of any convection pumping because of the tight spaces around the coil. It also suffers from heat generation in the aluminum rings placed in close proximity to the voice coil. While these are meant to serve a dual purpose of thermal conduction and distortion reduction, by virtue of the mechanism to reduce distortion they serve as a secondary of a transformer with the voice coil being the primary, and therefore must be carrying current and generating heat. On this driver the minimum impedance will reflect the added load and will be much higher than R_e.

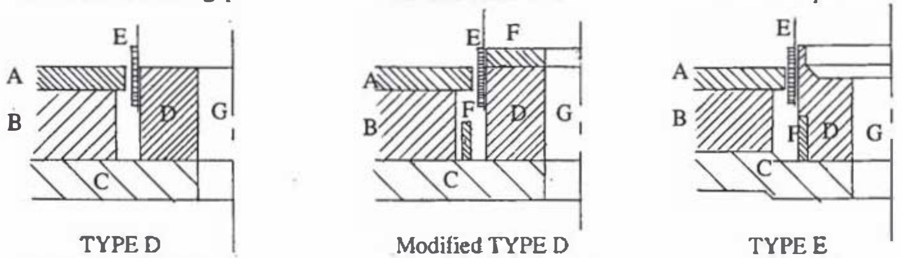
The second useful design (type A) has limitations in the type of input signal that will fully utilize the convection pumping from the cone. Clearly, *without* cone motion the exposed portions of the coil will conduct



TYPE A
convection cooled gap

TYPE B
encased voice-coil

TYPE C
under-cut pole



TYPE D
simple pot structure

Modified TYPE D
lower distortion version

TYPE E
extended pole
saturated pole tips

Fig. 4. Voice-coil magnetic gap configurations. A—top plate, steel; B—magnet, ceramic; C—backplate, steel; D—pole piece, steel; E—voice-coil, aluminum or copper; F—bucking rings for flux modulation reduction and inductance control, aluminum; G—vent (type A has three at periphery of pole piece).

poorly to the structure or the surroundings and will heat up. Conversely, *with* cone motion this design is very effective in dissipating heat. Because of the thinner top plate, and the position of the bucking ring placed far from the voice coil, very little heat other than that from the voice coil is generated. The minimum impedance of this driver is much closer to R_e. This driver also has the added advantage of short-circuiting the thermal resistance of the pot structure and dissipating heat directly to the ambient air.

Examining the other geometries reveals less ideal situations. In the case of the equal height or underhung voice coil (in types C and D), while the thermal paths are very good from the entire voice coil to the magnet structure, the coils are inherently short, meaning low thermal capacitance and lower surface area. Voice coils with a moderate amount of overhang (generally less than two-thirds of top-plate thickness) will do much better, especially if there is cone motion. With cone motion, during a certain portion of the duty cycle the coil tips will in fact be in the gap and conducting heat to the pot structure. Also, turbulence under the dome and spider, during cone motion, will help dissipate additional heat from the coil tips.

In designs other than type A, as the dome moves toward the structure, air is forced in two possible places, through the vent hole or past the voice coil in the gap. At the expense of increasing distortion, making the vent smaller will encourage air flow past coil windings, increasing convection cooling. In the case of smaller cheap loudspeakers with no venting, cooling for the given voice-coil size is very good, suggesting that good heat dissipation can be achieved at the expense of added low frequency over damping and distortion.

3 MEASUREMENTS

With the criterion for good heat dissipation being a large-surface-area coil with good conduction or convection paths, let us now look at actual measurements taken on a variety of different geometries. The figures presented are thermal resistances with different inputs from 100 to 500 W. Two types of input signals were used. A sine wave at the minimum-impedance frequency and a 50–500-Hz pink-noise signal. The loudspeakers were tested in free air. The purpose here was to show expected performance with and without cone motion. Of course, cone motion will vary depending on the spectrum used. For higher frequency spectra, interpolations between given thermal resistance values can be made, and for low-frequency inputs below 50 Hz the thermal resistance values could be extrapolated. 3τ is set equal to t_1, the point at which the thermal rise is 95% complete for the first RC pair. The power levels were based on power into cold minimum impedance. The real power used to calculate the thermal resistance values was derived from voltage and current. The temperature was derived from the change in dc resistance.

Table 1 reveals a number of interesting comparisons that can be made. Some of the more important conclusions are as follows:

1) Voice coils run cooler with pink noise rather than sine wave input.

2) Thermal resistance values drop as power is increased, suggesting a) greater conduction to the top plate as the voice coil nears the top plate due to thermal expansion, and b) greater convection cooling due to the turbulence at high cone excursions.

3) Larger voice coils run cooler than smaller ones.

4) A certain amount of voice-coil overhang is actually better than equal height.

5) Massive aluminum coils heat much more slowly, yielding better transient capability.

6) All devices show some thermal short-circuiting past the magnet structure at high signal levels, suggesting that some heat is dissipated by turbulence directly to air or that cone motion helps cool the frame.

7) All units had frame and pot structures of about the same mass and surface area and consequently similar R_m values and ΔT_2 values of about 2 h.

8) The convection-cooled coil design (type A) showed a clear short circuit of the pot structure thermal resistance at high powers ($R_m = 0.10$).

9) Thicker top plates provide better conduction from the coil.

10) Too much voice-coil overhang is detrimental.

11) Equal-height coils, with the exception of very tall gaps, are inferior to overhung designs and suffer greater distortion products.

4 POWER COMPRESSION

Having examined the heat dissipation character of loudspeakers and detailed the range of performance that now exists in the marketplace, the next step is to relate this to useful performance calculations. Clearly the voice coil is heating up and is never going to operate at room temperature. The dc resistance of the voice coil will rise with temperature according to

$$R_{e(\mathrm{hot})} = R_{e(\mathrm{cold})}(1 + 0.00393\Delta T) \tag{8}$$

In loudspeaker Thiele–Small parameters two important equations contain R_e,

$$Q_{es} = \frac{2\pi F_s M_{ms} R_e}{B^2 l^2} \tag{9}$$

$$N_0 = \frac{K B^2 l^2 S_d^2}{M_{ms}^2 R_e} \tag{10}$$

where

Q_{es} = electrical Q
F_s = resonant frequency, Hz
M_{ms} = moving mass of diaphragm and air load, kg
B = average flux density in length of coil, T
l = length of conductor in voice coil, m
N_0 = half-space reference efficiency, %
K = 5.44×10^{-2}
S_d = piston diameter, m^2.

Table 1.

	COIL DIA (IN)	TOP PLATE THICKNESS	COIL HEIGHT / WINDING WIDTH	COIL MATERIAL	37 300 W NOISE S	100 W C^0/W				300 W C^0/W				500 W C^0/W			
						MIN Z SINE		(50-500 Hz) NOISE		MIN Z SINE		(50-500 Hz) NOISE		MIN Z SINE		(50-500 Hz) NOISE	
						Rg	Rm	Rg	Rm	Rg	Rm	Rg	Rm	Rg	Rm	Rg	Rm
TYPE A	4	0.320	0.750/0.054	ALUM	37	1.10	0.33	0.73	0.26	1.06	0.31	0.65	0.15	1.02	0.30	0.58	0.1
TYPE B	4	0.350	0.800/0.048	ALUM	35	1.03	0.36	0.75	0.3	0.97	0.32	0.7	0.28	0.91	0.29	0.66	0.27
TYPE C	4	0.600	0.290/0.025	Cu	15	1.57	0.33	1.3	0.3	1.5	0.3	1.25	0.28				
	4	0.280	0.430/0.025	Cu	19	1.35	0.35	1.12	0.32	1.3	0.32	1.05	0.29				
	4	0.280	0.630/0.025	Cu	20	1.10	0.32	0.8	0.29	1.05	0.32	0.74	0.28	0.98	0.32	0.67	0.27
	4	0.280	0.750/0.025	Cu	24	1.10	0.33	0.81	0.3	1.04	0.31	0.75	0.3	0.97	0.3	0.69	0.26
	4	0.350	0.750/0.025	Cu	22	0.95	0.31	0.74	0.3	0.89	0.3	0.69	0.28	0.82	0.3	0.64	0.27
	4	0.280	0.950/0.025	Cu	42	1.30	0.34	1.15	0.31	1.25	0.33	1.07	0.29				
	4	0.350	0.600/0.025	ALUM	16	1.05	0.33	0.8	0.29	0.98	0.31	0.73	0.3	0.93	0.3	0.67	0.28
	4	0.350	0.950/0.025	ALUM	30	1.20	0.32	0.97	0.3	1.15	0.32	0.9	0.29				
	4	0.450	0.600/0.025	ALUM	15	1.00	0.35	0.75	0.32	0.92	0.33	0.72	0.29	0.85	0.33	0.69	0.28
	4	0.450	0.750/0.025	ALUM	18	0.95	0.31	0.71	0.3	0.87	0.3	0.67	0.28	0.81	0.31	0.63	0.27
	4	0.450	0.95/0.025	ALUM	23	0.97	0.34	0.7	0.33	0.9	0.35	0.67	0.3	0.84	0.32	0.62	0.28
	4	0.450	0.95/0.025	Cu	27	0.90	0.33	0.68	0.3	0.82	0.32	0.65	0.29	0.76	0.31	0.61	0.27
	4	0.600	0.60/0.025	ALUM	13	0.93	0.32	0.73	0.3	0.87	0.31	0.68	0.28	0.8	0.31	0.65	0.27
TYPE D	2.5	0.43	0.40/0.025	ALUM	16	2.44	0.36	2.13	0.33	2.38	0.36	1.96	0.3				
TYPE D	2.5	0.43	0.60/0.025	ALUM	18	2.00	0.37	1.72	0.34	1.92	0.36	1.52	0.32				
MODIF	2.5	0.43	0.80/0.025	COPPER	26	1.72	0.38	1.42	0.34	1.65	0.37	1.25	0.33				
TYPE E	3.0	0.50	0.60/0.030	ALUM	24	1.70	0.35	1.38	0.32	1.64	0.36	1.22	0.29				
	3.0	0.50	0.80/0030	ALUM	28	1.48	0.36	1.17	0.32	1.41	0.34	1.08	0.28				
	3.0	0.50	1.00/0.030	ALUM	32	1.32	0.36	1.08	0.33	1.27	0.34	1.01	0.27				
TYPE C	3.0	0.35	0.4/0.025	ALUM	20	2.38	0.38	2.09	0.34	2.31	0.36	1.92	0.33				
	3.0	0.35	0.6/0.025	ALUM	24	2.02	0.39	1.7	0.33	1.98	0.35	1.56	0.33				

As R_e rises, three effects take place. 1) The electrical Q_{es} rises, decreasing electromagnetic damping. 2) The half-space efficiency decreases, reducing expected output. 3) The impedance of the loudspeaker will, of course, rise and voltage sensitivity will decrease. This combination of maladies is called power compression. It is obvious that none of these things are desirable.

Let us now make a further examination of power compression effects by incorporating information from the previous discussion on heat dissipation. By virtue of Table 1 we can make reasonable estimates of thermal resistances and voice-coil temperatures for any power level and design type listed. The information that we really want is the voice-coil temperature, so that R_e can be extracted. From this the change in Q_{es}, N_0, and power compression can be calculated. The thermal resistance values can also give maximum output capability. We know:

$$Q = \frac{\Delta T}{R_0} \tag{11}$$

where

R_0 = given thermal resistance, °C/W
ΔT = temperature rise, °C
Q = real power, W.

Also

$$P_e = \frac{V^2}{Z} \tag{12}$$

and

$$Z = k_1 R_e \tag{13}$$

where

P_e = power into minimum impedance cold, W
Z = minimum impedance, Ω
V = voltage, V
k_1 = Z/R_e

So

$$P_e = \frac{V^2}{k_1 R_e} \; . \tag{14}$$

There will be a loss of power transferred as R_e rises with a constant voltage source,

$$Z_{hot} = Z_{min} + (k_2 \Delta T R_e) \tag{15}$$

where $k_2 = 0.00393$ (percent resistance rise per degree Celsius for aluminum and copper).

$$\frac{V^2}{Z_{hot}} = Q \tag{16}$$

$$V^2 = Q(k_1 R_e + k_2 \Delta T R_e) \tag{17}$$

$$V^2 = \frac{\Delta T k_1 R_e}{R_0} + \frac{k_2 \Delta T^2 R_e}{R_0} \tag{18}$$

$$k_2 \Delta T^2 R_e + k_1 R_e \Delta T - V^2 = 0 \tag{19}$$

$$\Delta T^2 + \frac{k_1}{k_2} \Delta T - \frac{R_0 V^2}{k_2 R_e} = 0 \tag{20}$$

$$\Delta T^2 + \frac{\Delta T k_1}{k_2} - \frac{V^2 R_0}{k_2 R_e} = 0 \; . \tag{21}$$

Solving we get

$$\Delta T = \frac{-(k_1/k_2) \pm \sqrt{(k_1/k_2)^2 + (4 R_0 V^2 / k_2 R_e)}}{2} \; . \tag{22}$$

This equation gives us a good way to find the temperature rise of any loudspeaker with any kind of input. The thermal resistance used is either R_G or $R_g + R_m$, depending on whether short- or long-term temperature is desired ($R_0 = R_G + R_M$). All that is needed is a voltage level, a dc resistance, and a minimum impedance.

These equations become useful when deciding thermal performance for a given power rating. Say we wish to design a 400-W loudspeaker, the maximum temperature our voice coil can handle is 300°C, and ambient air is 20°C. What thermal resistance R_0 is necessary? Let us say $R_e = 6\ \Omega$ and $Z_{min} = 8.0\ \Omega$. Then $400 = V^2/8$ and $V^2 = 3200$. We know that

$$V^2 = \frac{\Delta T k_1 R_e}{R_0} + \frac{k_2 \Delta T^2 R_e}{R_0} \; .$$

From this,

$$3200 = \frac{280(8/6) \cdot 6}{R_0} + \frac{0.00393(280)^2 \cdot 6}{R_0} \; .$$

Solving,

$$R_0 = 1.28\ °\mathrm{C/W}.$$

Therefore we must have $R_g + R_m < 1.28$ °C/W.

We can also calculate power handling knowing R_0 and maximum temperature. Let us use an example loudspeaker and set $R_0 = 1.50$. What is the maximum power handling?

$$V^2 = \frac{280(8/6) \cdot 6}{1.5} + \frac{0.00393(280)^2 \cdot 6}{1.5} \; .$$

Then $V = 52.2$ and

$$P_e = \frac{(52.2)^2}{8} = 341\ \mathrm{W} \; .$$

One note of caution: This is the power rating based on cold minimum impedance, as prescribed by the Audio Engineering Society. The real power that the driver is dissipating is much less.

Being able to calculate ΔT also allows us to directly compute power compression. Power compression, as stated earlier, will ensue due to a loss in half-space reference efficiency and to less drive from a constant voltage source into a rising impedance. Both are directly related to the rise in R_e due to the increase in temperature. The loss of efficiency will be

$$= \frac{1}{1 + k_2 \Delta T} \tag{23}$$

due to the rise in R_e. Q will reflect the amount of real power being fed to the loudspeaker. Therefore

overall output = SPL

$$\text{SPL} = \text{SPL}_1 + 10 \log Q - 10 \log(1 + k_2 \Delta T) \tag{24}$$

$$\text{SPL} = \text{SPL}_1 + 10 \log \frac{\Delta T}{R_0} - 10 \log(1 + k_2 \Delta T) \tag{25}$$

$$\text{SPL} = \text{SPL}_1 + 10 \log \left[\frac{\Delta T}{R_0(1 + k_2 \Delta T)} \right] .$$

where

SPL = sound pressure level, dB
SPL$_1$ = sound pressure level at 1 W, dB.

Taking ΔT to infinity shows that the maximum sound pressure level is

$$\text{SPL}_{\max} = \text{SPL}_1 + 10 \log \left(\frac{1}{R_0 k_2} \right) . \tag{27}$$

Power compression is then

$$\text{PC} = 10 \log P_e - 10 \log \left[\frac{\Delta T}{R_0(1 + k_2 \Delta T)} \right] \tag{28}$$

$$= 10 \log \left[\frac{P_e R_0 (1 + k_2 \Delta T)}{\Delta T} \right] \tag{29}$$

Using the earlier example let us calculate:

1) Maximum sound pressure level
2) Sound pressure level at 400 W
3) Power compression at 400 watts.

Given

R_0 = 1.28 °C/W
ΔT = 280°C
R_e = 6 Ω
P_e = 400 W
SPL$_1$ = 98 dB.

$$\text{1) SPL}_{\max} = 98 + 10 \log \left[\frac{1}{1.28 \times 0.00393} \right]$$

$$= 120.98 \text{ dB}.$$

2) SPL at 400 W

$$= 98 + 10 \log \left[\frac{280}{1.28(1 + 0.00393 \times 280)} \right]$$

$$= 118.18 \text{ dB}.$$

$$\text{3) PC} = 10 \log \left[\frac{P_e R_0 (1 + k_2 \Delta T)}{T} \right]$$

$$= 10 \log \left[\frac{400 \times 1.28(1 + 0.00393 \times 280)}{280} \right]$$

$$= 5.82 \text{ dB}.$$

These results are quite enlightening. A manufacturer might naively say that maximum output from this driver is 124 dB [98 + 26(400 W)], but in fact the output at 400 W is only 118.2 dB, and the maximum achievable (with hundreds of volts and extremely high temperature) is still only 120.9 dB.

So far we have simply addressed compression due to the temperature rise of the voice coil. Adding further insult, as the magnet structure heats up, the flux level will drop. Fig. 5 shows the flux loss versus temperature of Alnico, ceramic and neodymium magnets. To complete maximum long-term sound pressure level calculations, we will need to subtract the loss due to the fall in B field. If the R_m of our structure is on the order

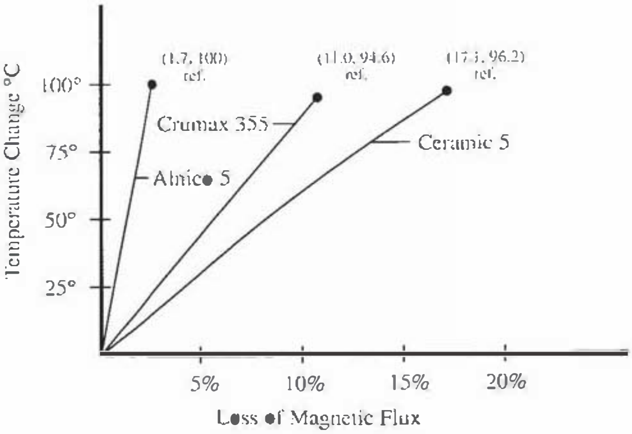


Fig. 5. Magnet flux loss versus temperature.

of 0.28°C/W, we then should obtain $\Delta T = 77.6°\mathrm{C}$ using Eq. (20). Using the curve for ceramic from Fig. 5, this corresponds to about a 14% loss of flux. Since B is squared in Eq. (10), the total compression due to magnet heating is

$$\mathrm{PC}_{\mathrm{mag}} = 20 \log(0.86) = 1.31 \text{ dB} .$$

Our final long-term calculations give

$$\mathrm{SPL}_{\max} = 120.98 - 1.31 - 119.67 \text{ dB}$$

$$\text{SPL at } 400 \text{ W} = 118.2 - 1.31 = 116.9 \text{ dB}$$

$$\text{total PC} = 7.13 \text{ dB} .$$

The final performance degradation is in the change in Thiele–Small parameters. More specifically, Q_{es} will change,

$$Q_{es} = 2\pi F_s M_{ms} \frac{R_e(1 + k_2 \Delta T)}{B^2 l^2} . \tag{30}$$

In this equation B will also change. Let us say our example loudspeaker has a Q_{es} of 0.30. At the end of a power test or a concert, this will have risen to

$$Q_{es} = 0.85 .$$

Fig. 6 shows the sample loudspeaker before and after full-term power compression.

Of additional interest is the very short-term behavior of the voice coil. The voice coil should heat slowly in the first few seconds. This will guarantee good transient behavior. The short-term behavior can be extracted from τ. Using $t_1 = 3\tau$ we can easily find τ. By inserting known values of R_g and τ into Eq. (5) we get

$$\Delta T = Q R_g \left[1 - \exp\left(\frac{t}{\tau}\right) \right] . \tag{31}$$

If we assume that in the first few seconds $Q = P_e$, we can make a reasonable guess as to transient ability. Let us compare the temperature at $t = 1$ s for our sample 400-W driver, with $3\tau = 20$ s for instance, with the type A design. $P_e = 400$ W for the sample driver, $R_g = 1.0$ and $R_m = 0.28$. Then

$$\Delta T = 400 \times 1.0 \left[1 - \exp\left(\frac{1}{6.7}\right) \right] \quad \Delta T = 64.4°\mathrm{C}$$

$$\mathrm{PC} = 2.1 \text{ dB}.$$

For a type A driver, $R_g = 0.6$ and $\tau = 12.3$. Then

$$\Delta T = 400 \times 0.6 \left[1 - \exp\left(\frac{1}{12.3}\right) \right] \quad \Delta T = 20.32 \text{ °C}$$

$$\mathrm{PC} = 0.64 \text{ dB} .$$

This example clearly shows the advantage of the low R_G and high τ of the massive aluminum coil and convection cooling.

5 CONCLUSIONS

Power compression is directly related to heat dissipation in loudspeakers. The most effective current methods for dissipating heat are as follows:

1) Using large-diameter massive aluminum coils to

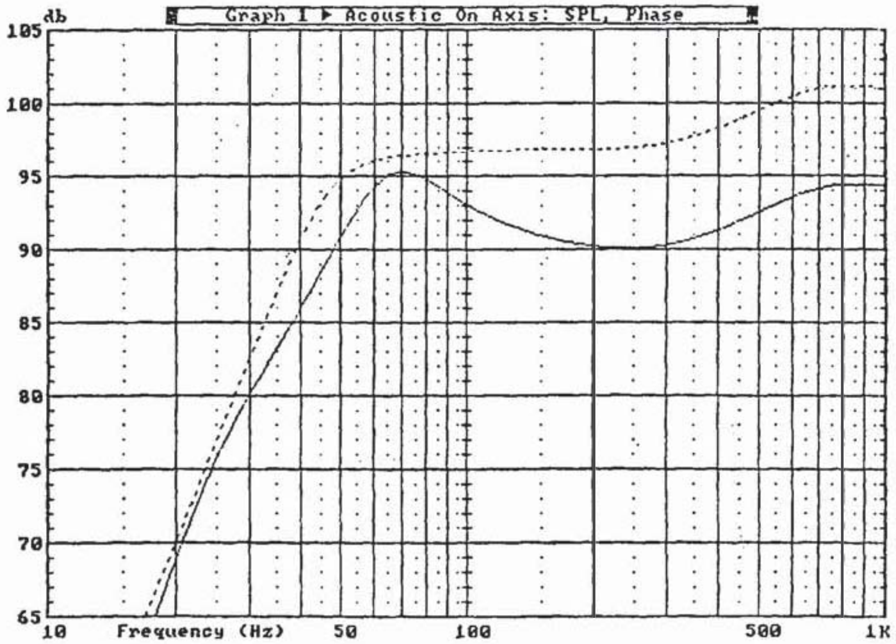


Fig. 6. Sample loudspeaker before and after compression. —— $Q_{es} = 0.85$; - - - - - $Q_{es} = 0.3$.

insure large surface area and high thermal capacity with minimum mass.

2) Using thick top plates or encasing coil in metal to insure good thermal conductivity paths away from coil.

3) Taking advantage of cone motion to convection-cool coil and bypass magnet-structure thermal path.

Item 2) has side effects which are not necessarily desired. Thick top plates are more susceptible to third harmonic distortion in the midband. This is due to a modulation distortion phenomenon, which is not explained in this paper or in previous work and must be taken at face value. It is described in further work by the author [10]. Encasing the gap with aluminum will only slightly increase thermal conductivity from the coil as the aluminum will act as a secondary in a transformer with the voice coil. The aluminum is carrying current and will heat up. With low distortion and low power compression as prime design criteria, the type A magnet structure, as shown in Fig. 4, appears to be the optimum economical solution.

It is clear, however, that even the best transducers will power compress and yield less than desirable performance at the limits of their power capacity. It therefore makes the most sense to operate drivers well below maximum power to achieve desirable performance. The ideal operating level will track with power handling, and drivers with high power ratings and good short-term capability (high τ and low R_g) will be the best choice.

6 IMPROVEMENTS

To achieve low power compression, clearly, better heat dissipation schemes are necessary. Based on information presented earlier, larger coils would provide some improvement, as would ferrofluid, but by probably only an incremental amount. Largercoils will, of course, weigh more, which will reduce efficiency and ferrofluids will have other adverse effects. Also, large coils require more magnetic strength, suggesting that this solution might not be economical. It appears that peripheral cooling devices such as heat pipes, refrigerated forced air, or similar devices are necessary to extract heat directly from the voice coil. Possibly a more interesting approach is the development of transducers with stationary coils that are directly heat sinked. This eliminates the insulating layer of the air in the magnetic gap. A cost-effective moving magnet structure does not exist yet, but is probably the most elegant solution to voice-coil heat dissipation. The final analysis is that to do significantly better than available drivers, radically new geometries will be required, and only time will tell if they can be implemented in a cost-effective manner.

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