solid state

A Hybrid Tube/MOSFET Headphone Amplifier

By Erno Borbely

This noted audio expert makes his popular hybrid amp design available for headphone use.

In the 1/98 issue of *Glass Audio*, I wrote about a hybrid tube/MOSFET line amp, which, because of its musical sound, became a very popular amplifier ("Low-Voltage Tube/MOSFET Line Amp," which also appears on www.borbelyaudio.com under Special Articles). DIY amateurs wished to use it in many different applications, such as CD buffer, I/V converter, power amplifier, and headphone amplifier. It worked very well in all line-level applications, but the second stage was not laid out for high-current operation, so driving headphones was not possible. I have therefore redesigned the circuit to allow high-current operation.

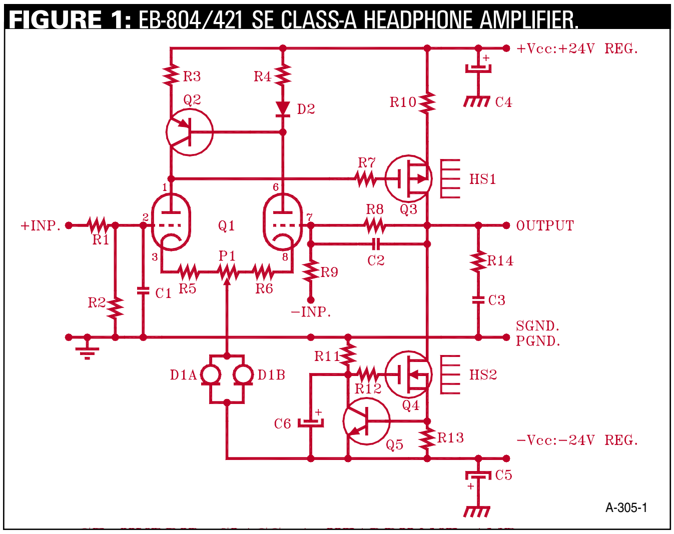
The result is the EB-804/421, a single-ended (SE) pure Class-A amplifier, capable of driving headphones between 32 and 600Ω. The amplifiers need ±15 to ±24V regulated supplies at 160/100mA and 6.3V DC at 300mA for the tube heater. I recommend feeding the amps from separate supplies. The PCB for one amp is 90 × 80mm.

CIRCUIT DESCRIPTION

The schematic is shown in *Fig. 1*. The topology is the same as the hybrid tube/MOSFET line amp. Q1 is a double triode that operates as a differential amplifier, with approximately 2mA in each of the triodes. A constant-current diode D1, which supplies the source current to the differential amp, includes two J508 or E-202 diodes in parallel. You can also use a single J511, which delivers 4.7mA.

The two anodes, which produce out-of-phase signals, are converted to a single-ended signal using a current mirror composed of Q2, D2, and resistors R3/R4. Q3, a P-channel MOSFET in TO-220 package, is used in common-source mode as a Class-A single-ended second stage. I replaced its drain resistor with a second constant-current source, supplying the Class-A current of 100 or 160mA.

FIGURE 1: EB-804/421 SE CLASS-A HEADPHONE AMPLIFIER.



The constant-current source, which increases the gain and improves the linearity of the second stage, is made up of Q4, an N-channel MOSFET in TO-220 package, and its associated components. I used the Hitachi 2SJ79 and 2SK216 for Q3 and Q4, respectively. You can also use the Toshiba 2SJ313 and 2SK2013, but note that the pinout is different from the Hitachi (GDS versus GSD).

PHOTO 1: EB-804/421 PC BOARD.

The amplifier can work with a ±15V to ±24V supply. The maximum dissipation allowed for Q3 and Q4 is 2.4W each, so the supply voltage determines the maximum current. At ±24V the current is 100mA and at ±15V it is 160mA. Resistor R13 sets the current: it is 6R8 for 100mA and 3R9 for 160mA.

You must heatsink Q3 and Q4. I am using the SK76–37.5 with 8K/W thermal resistance. The temperature on the heatsinks is about 55° C, so proper ventilation is absolutely necessary! The PS/regulator I recommend for the hybrid tube/MOSFET headphone amplifier is the EB-802/243.

The input tube requires a 6.3V/350mA heater supply. Use a well-regulated/low-ripple supply for this (EB-793/204 is recommended). I recommend that you ground the negative side of the heater supply to the PGND on the PCB.

LINEARITY NOTES

The input tube dominates the overall distortion characteristics of the amplifier. Tubes of different manufacturers produce different amounts of distortion. I have tested the ECC86 from Telefunken and Ultron, ECC88 from AEG, E88CC from Tungsram, and 6922/6H23П, a Russian military tube. All worked fine, but the difference in THD can be 6-10dB!

The Russian 6922/6H23П produced the lowest THD. We are shipping the kits with these tubes. Nevertheless, I recommend that you try different types of tubes and select the one you like best.

Note also that the tube can pick up hum from mains fields. Again, tubes from different manufacturers show different sensitivity to these fields. It would help to use a shielded tube socket; however, it is difficult to find one for PCB mounting.

Finally, it is a good idea to switch on the heater before you apply the ± supply to the amplifier. This has nothing to do with cathode stripping, but with the DC operation of the amplifier. As long as the heater is off, the input does not function even if you apply the ± supply. Consequently, the DC feedback loop is inactive and the output is not sitting at 0V.

Only after the heater is on can the

HEADPHONE POWER REQUIREMENTS

There appears to be much misunderstanding concerning the power required to drive a headphone. This is usually due to the fact that headphones have different impedances, the lowest is around 30Ω and the highest 600Ω. The headphone impedance is no indication of the quality of the headphone, but it has a major influence on the amplifier from which you can drive it.

Headphone sensitivity is specified in sound pressure level (SPL) when you apply 1mW of power to it. Given the impedance of the headphone and the maximum SPL you would like to achieve, you can easily calculate the necessary drive power.

For the sake of illustrating the power requirements, consider a low impedance headphone first, for example, 40Ω. To produce 1mW into 40Ω you need a current of:

$$I=\sqrt{(P/R)}=\sqrt{(1mW/40\Omega)} = 5mA$$

The necessary voltage to produce this current in 40Ω is:

$$U = I \times R = 5mA \times 40\Omega = 200mV$$

So far so good. I am sure all headphone amps can deliver this much current at this voltage swing.

Now for the maximum SPL. This particular headphone is specified at 256mW maximum power, which is achieved at a current of I = 80mA and a voltage of U = 3.2V. The SPL difference between 1mW and 256mW power is given by the formula:

$$\text{SPL diff.} = 10 \log (P1/P2) = 10 \log (256/1)= 24dB$$

So the maximum SPL with 256mW power will be 100dB + 24dB = 124dB.

You can draw some general conclusions from these results. You can see that you need a relatively moderate voltage swing, but a rather hefty current to produce this SPL in a low impedance headphone. In fact, some 40Ω headphones need even more power to achieve maximum SPL. One, in particular, is specified at 102dB at 1mW and 440mW for maximum SPL. The 1mW current/voltage requirements are the same as the previous one, but to achieve 440mW you need:

$$I=\sqrt{(440mW/40)} = 104.9mA$$

$$U = I \times R = 104.9mA \times 40 = 4.2V$$

The SPL difference from 102dB will be:

$$\text{SPL diff.} = 10 \log (440/1) = 26.4dB$$

And the maximum SPL will be: 102dB + 26.4dB = 128.4dB.

Note that you now have almost ½W of power here, with a relatively moderate voltage swing, but quite a lot of current! Of course the question is: do you ever need an SPL of 128dB? Many headphones operating at maximum power might cause damage to your hearing!

Now let's look at the other end of the impedance range: 600Ω. A typical example includes sensitivity of 98dB SPL at 1mW input and a maximum power of 80mW.

The current requirement for 1mW is:

$$I=\sqrt{(1mW/600\Omega)} = 1.29mA$$

And the necessary voltage is:

$$U = 1.29mA \times 600 = 0.77V$$

For maximum power you need:

$$I=\sqrt{(80mW/600\Omega)} = 11.55mA$$

$$U = 11.55mA \times 600\Omega = 6.93V$$

The maximum power will produce an SPL difference of:

$$\text{SPL diff.} = 10 \log (80/1) = 19dB$$

And the maximum SPL is: 98dB + 19dB = 117dB.

Although the maximum SPL is relatively low for this headphone, the voltage has increased considerably compared with the 40Ω headphone. On the other hand, the current requirement is relatively low. Obviously headphones with impedances between these values fall between these two as far as current and voltage requirements are concerned.

PORTABLE HEADPHONE AMPLIFIERS

Headphone amps, just like speaker amps, are available in many varieties: tube-based, semiconductor-based, and mixtures of both technologies. Most mid-fi CD players, receivers, and amps also offer headphone outputs. And, of course, all portable Walkman-type CD players, cassette players, and radios use headphones.

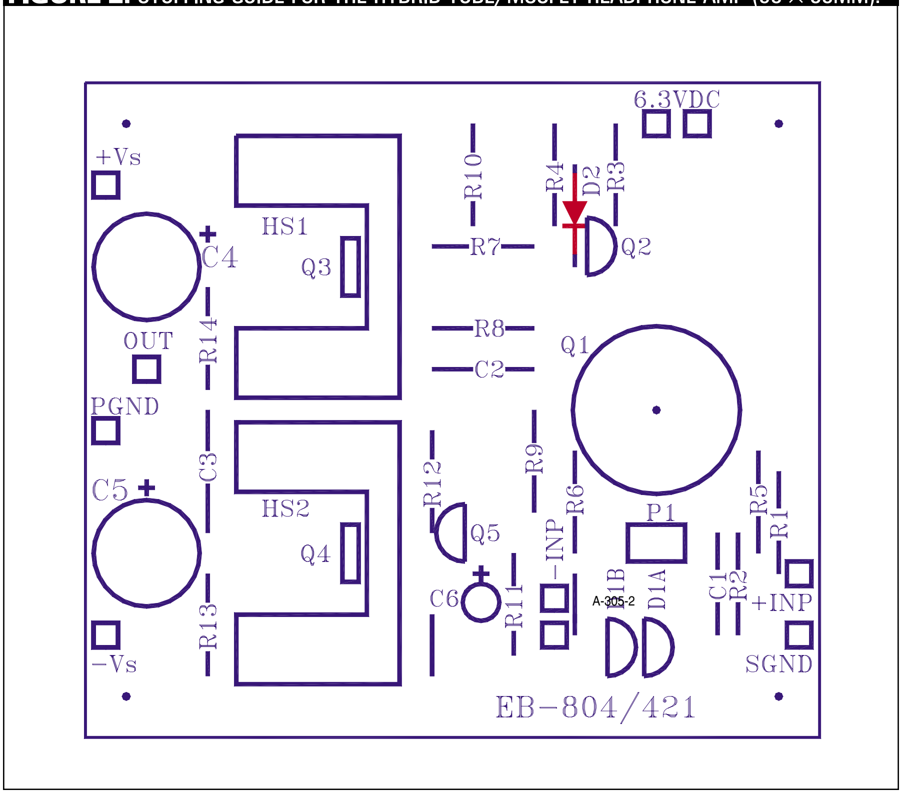
The most problematic of these is the last group, because they are operating from batteries. Of course, nothing is wrong with batteries per se, except for the amount of voltage/current available for the headphone amp.

Consider for a moment the voltage/current requirements for the two types of headphones described previously. The 40Ω unit required 3.2V RMS to generate 124dB SPL. Since we are talking about sine waves here, the 3.2V RMS is equal to 3.2 × 2.82V peak-to-peak, i.e., 9.024V for the amplifier. And this is a theoretical value.

Practical amplifiers that operate with a 9V supply cannot deliver 9V peak-to-peak audio signal, because most audio amps are not capable of working "rail-to-rail," i.e., from zero to 9V. In addition, the 9V battery would need to deliver 80mA for just the audio amp, not output stabilize to 0V. Alternatively, you can leave the heater on all the time or in a stand-by mode with—say—4V, in which case you can apply the full heater voltage and the supply voltage simultaneously.

The feedback resistors R8 and R9 set the closed loop (CL) gain of the amp. Normal gain is 10×, or 20dB. Changing R9 can change this gain. CL output impedance is 15Ω. Equivalent input noise depends on the tube used and is 1.2–1.5μV!

FIGURE 2: STUFFING GUIDE FOR THE HYBRID TUBE/MOSFET HEADPHONE AMP (90 × 80MM).



The maximum output power into different loads depends on the supply voltage and the available current from Q4. With ±24V and 100mA in the second stage, the amp delivers >100mW into 32Ω and >250mW into 600Ω at 1% THD. With ±15V and 160mA the power into 32Ω increases to 300mW at 1% THD.

The maximum power is limited by the available current at low load impedances and by the available voltage swing at high impedances. If your headphones are low impedance, you should operate the amplifier at ±15V with 160mA in the second stage, and if they are high impedance, use a ±24V supply with 100mA. Since high impedance headphones require less power than the low impedance ones, the ±15V operation will probably give more than enough power for ear-shattering SPL over the whole impedance range.

ASSEMBLY

Figure 2 shows the stuffing guide for the hybrid tube/MOSFET headphone amplifier. Start the assembly by installing the solder pins, jumpers, and then

taking into consideration the rest of the electronics.

And this is not the end of the story. The Walkman-type devices are usually operating with two 1.5V batteries, for a supply of 3V total. Assuming that the audio amp would be able to work "rail-to-rail," the equivalent audio signal would be 3/2.82 = 1.06V RMS, and you could generate a maximum current of:

$$I = 1.06/40\Omega = 26.5\text{mA}$$

This would give a maximum power of:

$$P = U \times I = 1.06\text{V} \times 26.5\text{mA} = 28.1\text{mW}$$

And SPL difference would be:

$$\text{SPL.diff.} = 10 \log 28.1 = 14.5\text{dB}$$

And the maximum SPL: 100dB +14.5dB = 114.5dB, which is actually "only" 10dB less than the maximum. However, remember that in most cases the audio signal would be less than the one calculated, or the amp would already be clipping at a lower value. In a 32Ω headphone with 100dB SPL for 1mW input, the maximum power would be 35mW and the maximum SPL would be 115dB!

Real-life ICs, made specifically for low-voltage operation, will usually deliver less than this. Look up the National LM4911, which is a stereo headphone amp—it delivers 25mW into 32Ω at 1% THD from a 3V battery (12mW from 2.4V). This means that just a bit over 80% of the battery voltage is "converted" into audio! I bet most of the Walkman-type devices don't deliver much more than 10–15mW of "clean" audio!

What would happen if you connected a 600Ω headphone to this amp? The maximum current would be: 1.06/600 = 1.77mA, the maximum power: 1.06V × 1.77mA = 1.88mW. The SPL difference is:

10 log 1.88 = 2.74dB and the maximum SPL is 98dB + 2.74dB = 100.74dB.

Obviously, 600Ω headphones are less suited for this kind of application. For amps with low supply voltage, you need to use low-impedance headphones, assuming, of course, that the amp can deliver the necessary current.

Headphone amps operating from ±9V batteries fare much better in terms of maximum power. Assuming an 80% ratio between battery voltage and audio signal, such an amp could deliver over 600mW into a 40Ω headphone. Of course, the battery would also need to deliver the necessary current (over 120mA!), and the question is how long it would be able to do that? The same amp would manage only about 40mW into a 600Ω headphone, so even an amp working with ± 9V power supply cannot cover the whole impedance range.

In addition to the problem of available power, most of the low-voltage, battery-operated headphone amps are working with very low bias current to save battery life. This means in most cases Class-B operation. Now it's well known that Class-B is far from ideal in terms of sound quality due to crossover distortion, but there is really not much you can do when the amp must be portable and operate from low-voltage batteries. Still, there are many people listening to portable devices, so it cannot be all that bad!—**EB** all the resistors (including the trimpot P1). If you have selected ±15V operation, then resistor R13 = 3R9 and R10 = 7R5. If the supply voltage is ±24V, then R13 = 6R8 and R10 = 33R.

Next install Q2, Q5 and diodes D1 (A/B). Mount Q3 and Q4 on the heatsinks with insulator and install them on the board. Make sure the MOSFETs are properly tightened to the heatsink. Then install the tube socket and all the capacitors, with C4 and C5 being the last ones. Finally, plug the tube into the socket.

SETUP PROCEDURE

If possible, test each amplifier separately before installing it in the chassis. This simplifies measurements, adjustments, and, if necessary, component changes. If you have access to a scope, connect it to the output of the amp and check whether radio frequency (RF) oscillations are present. If you have a complete audio instrumentation in your workshop, perform the usual gain, frequency response, noise, total harmonic distortion (THD), and intermodulation distortion (IM) measurements.

Connect the +INP and the –INP to SGND. Apply the appropriate supply voltage (±15V or ±24V) and the 6.3V DC heater voltage to the amplifier. Connect a digital voltmeter (DVM) across R13 and check the voltage drop. It should be 0.62–0.65V. This sets the current to approximately 100mA or 160mA in the second stage, depending on the value of R13.

Let the amp run for about 20 minutes before you adjust the offset. Connect the DVM to the output of the amplifier and set the offset voltage to 0V with P1. This completes the DC adjustments.

The EB-804/421 kit is available from North American representative Larry Black; for US/Canadian customers, see www.audiokits.com. Other countries can order the kit directly from Borbely Audio, www.borbelyaudio.com. ***aX***

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PARTS LIST
EB-804/421

Resistors, Trimpot

R1,R7,R12	100R
R2	1MEG
R3,R4	499R
R5,R6	47R5
R8	10k, RN60
R9	1k1, RN60
R10	33R, RN60 (±24V) 7R5, RN60 (±15V)
R11	10k
R13	6R8, RN60 (±24V) 3R9, RN60 (±15V)
R14	47R5
P1	100R Copal

All resistors non-magnetic Dale CMF 135 and RN 60.

Capacitors

C1 (Optional)	100pF, 160V PS
C2	10pF, 160V PS
C3	1000pF, 160V PS
C4,C5	220µF, 35V
C6	100µF, 25V ROE EKO

Tube, Semiconductors

Q1	ECC86/6GM8, ECC88/ 6DJ8, E88CC/6922, 6H23П-EB
Q2	2SA872
Q3	2SJ79 INS.
Q4	2SK216 INS.
Q5	2SC1775
D1	J508 or E-202 (two in parallel)
D2	1N4148

Miscellaneous

PCB	EB-804/421
HS1,HS2	SK76-37.5

12 × 1mm solder pins
4 × M3 screws, nuts
2 × 9-pin PCB tube socket
Mounting hardware