Tuono: PP PL504 Amplifier

This author's amp design unleashes the thunderous sound of PL504 tubes in a push-pull configuration.

By Claudio Rosada

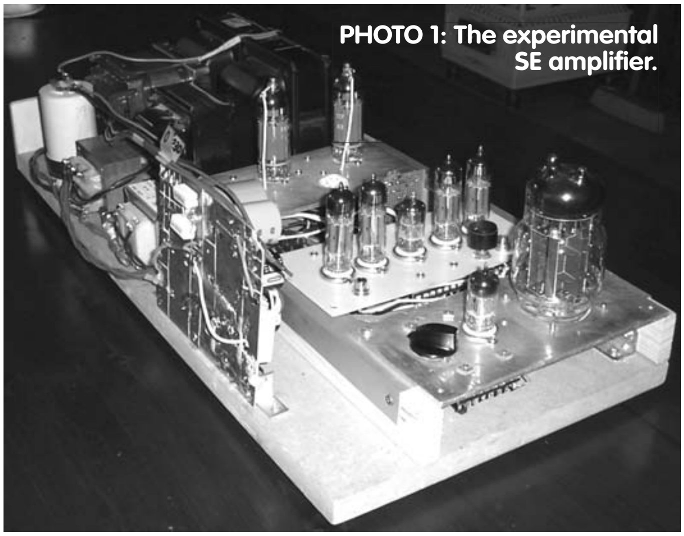


PHOTO 1: The experimental SE amplifier.

There are, in my opinion, some basic ingredients that you must combine to produce a good amplifier. First of all, you must look for a circuit with inherent linearity, avoiding as many "tricks" as possible to improve instrumental performances. Furthermore, an amplifier must be capable of driving "normal" speakers.

It is possible to derive from these generic principles some important technical recommendations. First of all, the device type: tubes and especially triodes have a good intrinsic linearity. Even transistors could be linear, but the very high parameter dispersion of these devices normally doesn't permit the use of simple circuit topology. So feedback is mandatory to produce stable and repetitive performances. I believe that the famous "tube sound" is highly due to the circuit topology.

Thus triode tubes, or triode-connected pentode tubes, are preferable, and global feedback must be avoided. I prefer to design amplifiers capable of driving "normal" speakers. From the electrical point of view, it means that the amplifier must feed the appropriate sound level speaker with 88–90dB efficiency, providing the current required at the minimum impedance point of the speaker.

For these reasons, I try to have at least 10W of output power and to limit the output impedance. The combination of these requirements is a good starting point for a design, but, unfortunately, they are in conflict with themselves! In fact, it is not easy to have low impedance and high power using just triodes without global feedback.

In the last few years I designed two amplifiers following these requirements. The first one was single-ended (SE) using the 6C33 tube with a high load. The second one was push-pull (PP) featuring the PL504 beam pentode in triode configuration. This article focuses on the latter.

Because I built this amplifier for a friend, I briefly discussed his requirements with him. He intended to have just one device replacing his existing transistor-based amplifier with three line inputs and one phono input (for just MM pickups). My basic idea was to design a modular unit to be used as either the final amplifier or as an integrated amplifier adding a preamplifier stage and an optional phono section. The volume control and three line level unbalanced inputs complete the system. The power supply is designed in modular format as well; only minor adaptations are necessary to move from one configuration to the other.

In the following paragraphs I'll describe the design starting from the final stage, because in a logic flow, each stage defines the requirements of the previous one.

THE OUTPUT STAGE

In the last few years I bought some PL504s for around $1 each. This tube was widely used in the past as a "beam" amplifier in TV receivers, so you can still find it at a reasonable price. The PL504 has a mechanical structure similar to the well-known EL34, apart from the anode

TABLE 1: PL504 PERFORMANCE IN SE CONFIGURATION.

					Load 600Ω		Load 1200Ω	
N	Va	Ia	Vg	Pd	P_{max}	THD@ P_{max}	P_{max}	THD@ P_{max}
1	128	115	−14	14.7	1.08	4.86	0.71	3.9
2	140	125	−15	17.5	1.15	4.6	0.74	3.86
3	172	100	−23	17.2	2.46	5.72	1.56	4.24
4	185	100	−25	18.5	3.1	6.0	2.0	4.41
5	212	100	−30	21.2	4.3	5.2	2.9	3.4
6	230	90	−35	20.7	5.5	5.8	3.6	3.6
7	230	85	−36	19.5	5.5	6.1	3.7	3.6
8	248	80	−40	19.8	6.6	7.0	4.5	4.0
9	242	85	−38	20.6	6.0	7.0	4.2	4.0
10	240	80	−38	19.2				

on top of the glass bulb and the unusual heater voltage of 27V. The dissipation is only 16W typical (22.5W absolute maximum), but the big advantage of this tube is the low (compared to EL34 or similar) internal resistance in triode connection (ranging from 200Ω to 500Ω). Also, linearity in triode connection is appreciable.

Unfortunately, there are not many designs based on this tube, so I decided to start evaluation in SE configuration, in order to better define a suitable working point and dynamic load. I built a complete amplifier (**Photo 1**) to evaluate both electrical and acoustical performance. I used a tunable fixed-bias circuit to change the grid bias, and assembled a tube based (using 6C33 triode as series regulator and a 12AX7 as error amplifier) variable voltage-regulator circuit (front of photo) to change the anode voltage.

The driver stage was the first prototype of the one described in the following. I varied the effective load simply by changing the resistive load on the output transformer. You can find the result of such experiments in **Table 1**.

As you can see, output power increases with the anode voltage, but the more interesting point is in the range of 240–250V, which is much higher than the one I was expecting from just looking at the curves. What is not evident in the table is that a further increase in anode voltage is not convenient, because the interdiction area of the tube will increase the distortion, providing no further benefit in terms of maximum output power. The conclusions of this experiment are that point numbers 8/9 are good candidates for the working point, while as far as the dynamic load is concerned, increasing the load produces limited effects on the distortion, while highly limiting the output power.

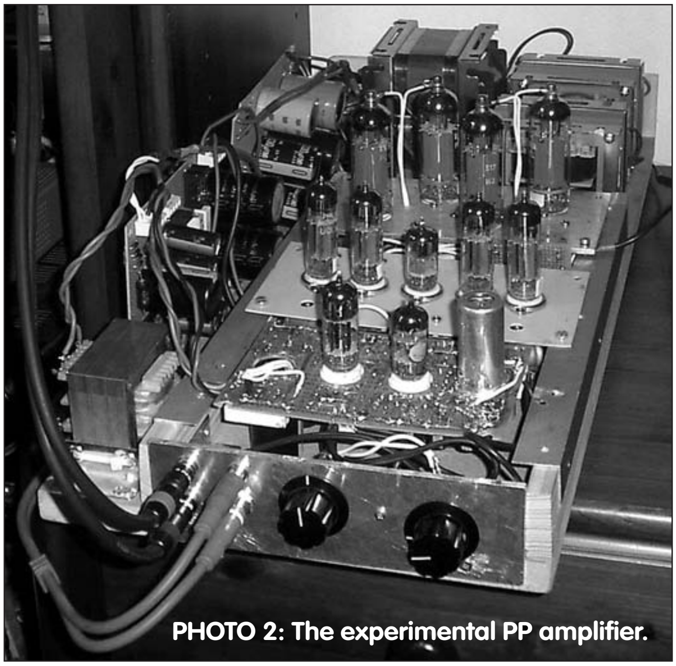


PHOTO 2: The experimental PP amplifier.

So I decided to use point number 10 with a dynamic load of 1200Ω. Someone may note that the dissipation in this point is 19.2W, much more than the typical 16W. To be honest, I don't know the real effect on the tube life of this condition. But considering that the absolute maximum value is 22.5W, I believe that this stress will not affect the tube life much.

Another important result of my SE experiment was the evaluation of driving capability required for the PL504. In fact, this tube, when dynamically driven, is sinking current, even at negative grid point. I was not able to characterize such current, so I cannot provide any figure about it, but I concluded that a high current driver was highly recommended for such a tube. **Table 2** shows the THD+N performance versus output power of the SE configuration for point n.5.

In order to fulfill the requirement of power in excess of 10W, one tube is not enough, so you must look for a parallel SE or PP configuration. After some trial and error with PSE configuration, I turned to PP, in order to investigate the performance and acoustic results that this topology can provide. All the experimentation done on the SE configuration was very helpful in defining the requirements of the output transformer for the PP configuration and of the driver stage.

THE OUTPUT TRANSFORMER

The requirements for this component are: 1) push-pull configuration; 2) dynamic impedance in the range of 1200Ω for each tube (resulting in 2400Ω rail to rail); 3) maximum output power at least 15W at 30Hz; 4) 20kHz bandwidth at full power. Even if this type of device is available on the market, I decided on a custom transformer. So I provided my requirements to a friend who has good experience in designing audio transformers. A few weeks after the first two samples were available, I started experimenting with the push-pull configuration. I measured a total primary winding around 64Ω.

The transformer was a device using oriented grain iron 0.3mm thin with an E/I shape and secondary winding implemented in double wiring. I measured a primary winding resistance around 32Ω, so if you use a different transformer, you might need to rearrange the power supply. The winding ratio for the whole primary winding is 18.54, resulting in an effective rail to rail load of 2750Ω on an 8Ω load.

THE INVERTER/DRIVER STAGE

The following requirements are necessary to feed the output stage: a) output dynamics in the range of 40V pick corresponding to 28.4V RMS; b) high driving capability to feed grid current; c) low distortion (you can put a limit of 1% at maximum modulation); d) full audio bandwidth (obvious); e) good dynamic balance over the full spectrum. I spent some time analyzing the existing inverter stage, and concluded that all these requirements cannot be fulfilled with only one stage at a reasonable cost. In fact, even if transformer-coupled or LC-coupled stages can probably provide the required current, they increase the complexity and cost of the design too much. So I determined that a cathode-follower stage was a good candidate for the grid feeding. Considering the variety of possible inverter stages, I prefer the Smith model for its symmetrical look.

Unfortunately, the Smith inverter can provide a good balance only when the cathode load of the two tubes approaches the infinite value. Mark Kelly's article in *Glass Audio*[1] offers the right idea. In

TABLE 2: PL504 PERFORMANCE IN SE CONFIGURATION AND POINT 5.

Power	THD+N at 600Ω	THD+N at 1200Ω	THD+N at 2400Ω
0.1	1.1	1.1	0.75
0.2	1.3	1.1	0.97
0.5	2.0	1.6	1.6
1	2.9	2.5	2.6
2	4.4	3.7	
4	6.8		

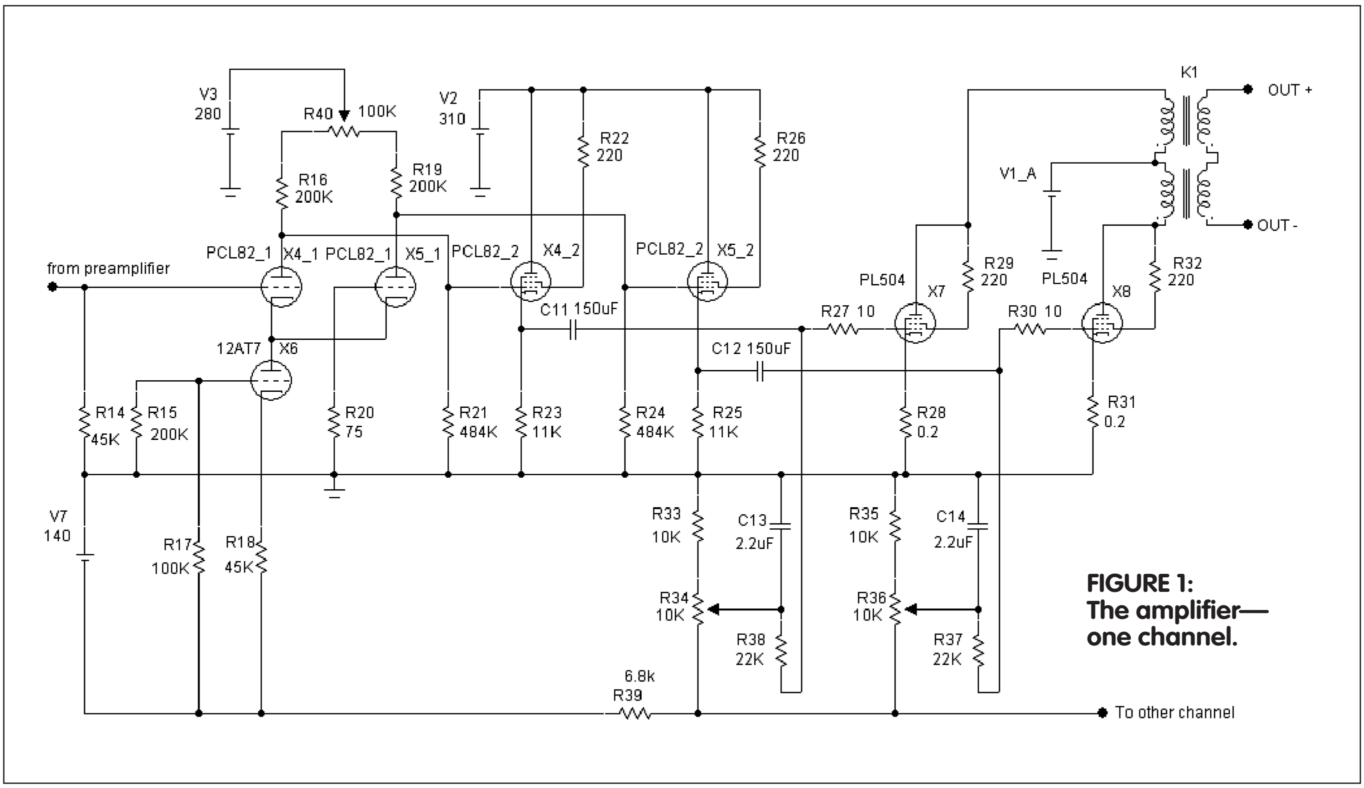
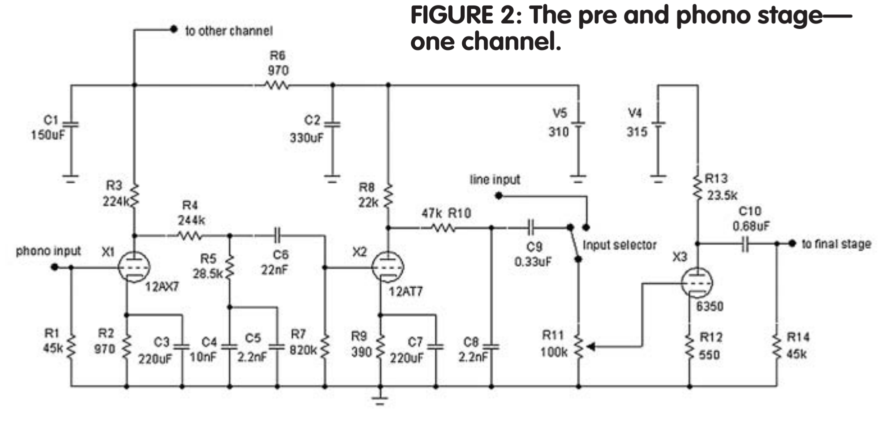


FIGURE 1: The amplifier—one channel.

fact, if you replace the resistive load with an active load, the balance of the Smith inverter can be highly improved. Such an active load can be implemented very simply with a triode, adding just a double triode component to the parts list. The combination of Smith inverter and cathode-follower current buffer make possible a DC coupling between the two stages, thus reducing the number of capacitors in the signal path.

This solution complicates the design, because now the two stages are strongly coupled and any deviation on the bias of the first stage impacts the second one. To implement the circuit topology previously defined, you have basically two different possibilities: a) use one high-mu double triode (e.g., 6SL7 or 12AX7) for the Smith inverter and a medium-mu low-impedance double triode (e.g., 6SN7 or 12AU7) for the buffer; b) use two asymmetric double triodes. Because I recently bought some UCL82 triode/pentode tubes, I decided on the second alternative.

FIGURE 2: The pre and phono stage—one channel.



The xCL82 family, which is widely known in Europe, is available with three different heater voltages: 6.3V = ECL82; 16V = PCL82; 50V = UCL82. The equivalent US versions are 6BM8, 16A8, and 50BM8. Due to the wide dispersion of these tubes in the past, they are still widely available as NOS at reasonable cost. The tube was originally designed for audio applications and mainly used in TV and radio receivers.

The pentode section of such a tube, when connected in triode configuration, provides a very low impedance drive, in the range of 250Ω. After fine-tuning, I chose the following working points for the two sections: Vg = –1.5V, Va = 300V, Ia = 0.6mA for the triode; Vg = –27V, Va = 230, Ia = 12mA for the pentode. The dissipated powers are 0.180W and 2.76W, well beyond the limits (1W and 7W, respectively).

The polarization current for the Smith inverter is obtained with a 12AT7; it is polarized in order to provide the 1.2mA required. Because the xCL82 tubes were used only in the triode/pentode configuration, no standard documentation is available for the triode connection of the pentode section. But this tube is widely used by Italian DIYers, and such documentation was published some years ago in an Italian magazine[2]. Because the Smith inverter is doing even harmonic cancellation, in order to obtain the best performances, a dynamic balance of the stage is helpful.

While static balance is good—because the xCL82 tubes were produced with high quality, which also means low parametric dispersion—it works on dynamic balance in order to improve harmonic distortion. But in order not to complicate the stage too much and to reduce the tuning operations, I suggest you simply buy a few more tubes and try to exchange them until you achieve a good combination of performances for the two channels (left/right). The distortion results of such a stage are presented in **Table 3**. I measured adding my distortion analyzer (with 100kΩ impedance) in parallel to the grid load of the final stage.

As you can see, because the instrument is doing the THD plus noise measure, the low-level signals are penalized by the residual power-supply ripple (refer to the power-supply section for more details). The driver/inverter stage has a total gain of 21.5 (and a maximum acceptance of 1.5V peak in class A1 corresponding to 1.06V RMS), so the required input signal to drive the final stage at full power in class A1 (corresponding to 38V peak) is approximately 1.76V peak. This means that at full power the triode section of xCL82 will be slightly driven in positive grid. This should not be a problem because the recommended bias in the data sheet is Vg = 0V.

To be honest, I tried without success to limit the working condition to a pure class A1 operation, but, unfortunately, any attempt to do so (due to DC coupling) impacts the bias of the pentode section, thus limiting the dynamics of the second stage. This operation in class A2 of the first stage limits the use of the high-impedance preamplifier section. Sensitivity should not be a problem for a CD player, but it is still far from the standard for an integrated amplifier (it should be more properly in the range of 0.5V RMS or so). In some cases, a preamplifier section might be necessary.

THE PREAMPLIFIER STAGE

My idea, as stated at the beginning of the article, was to build a modular integrated amplifier, so I added the pre stage just to have a better sensitivity. Most potential users don't really need this stage at all. The requirements for the preamplifier section are: a) low gain, in the range of some units; b) low impedance in order to drive in class A2 the further stage without degradation. For this simple stage I immediately chose the single-ended configuration with RC coupling. There are many different low-mu and low-impedance tubes that you can use in such an application—most of them designed for audio.

I decided to try a relatively unknown and inexpensive tube: the 6350 twin triode. As stated in the data sheet, this medium-mu twin triode was designed for use in electronic computers and other "on-off" control applications, involving long periods of operations under cutoff conditions. The tube is manufactured using high-quality materials and it is deeply tested. Unfortunately, according to my experience, this tube has two important drawbacks for audio applications: It is highly microphonic and sensible to heater noise injection. The tube has a relatively good linearity when used in low signal applications, such as preamplifier.

After analyzing the curves, I fixed the following working point: Vg = –4.35V, Va = 115V, Ia = 7.9mA. The resulting power is 0.9W per triode, far from the maximum value of 7.7W total. The tube has a mu of 18 and an internal resistance in the range of 4kΩ. When used in my SE configuration—without the bypass capacitor on the cathode resistor—the effective gain of the stage drops to the range of 10 (I measured 9.8 for both channels), which is more than needed, providing to the whole amplifier a sensitivity of 122mV RMS at full power.

The distortion performances under those conditions and with the effective circuit load are presented in **Table 4**. I measured adding my distortion analyzer in parallel to the grid load of the Smith inverter stage. As in the previous measurements the low-level signals are penalized by the residual power-supply noise. Note that distortion is very low (around 0.1%) as long as the further stage is in pure class A1 operation, while it increases when its grid starts to sink current.

You must use the tube with a DC heater to avoid excessive hum injection, and the tube is also very sensitive to mechanical vibration. In order to reduce the pickup effect to an acceptable level, install two dumping rings on the tube in case of vertical installation, while in horizontal installation they should not be necessary. If you adopt these precautions, the tube will provide a good performance for a reasonable cost.

THE PRE-PHONO STAGE

I added this stage at the end of the design to provide a direct turntable connection with pickup having sensitivity in the range of MM types. I think that designing a tube-based phono preamp is probably the most difficult challenge for a DIYer. In fact, the very low level of the incoming signal, its equalization, and all the potential problems related to ground loops—magnetic coupling, tube microphonicity, and so on—greatly limit the performance of such devices.

I tried to solve the problem by embedding the phono stage, including the preamplifier stages and their power filtering, in a very compact form. I chose the topology that is sometimes considered in the DIY community as the best

TABLE 3: UCL82 BASED DRIVER/ INVERTER PERFORMANCES.

Output volt [V RMS]	THD+N left	THD+N right
1	0.97	0.82
2	0.48	0.39
5	0.21	0.24
10	0.22	0.39
20	0.58	0.79
30	1.28	1.36

TABLE 4: 6350 PREAMPLIFIER SECTION.

Output volt [V RMS]	THD+N left	THD+N right	Amplifier output power [W]
0.1	0.32	0.34	
0.2	0.18	0.19	
0.5	0.10	0.11	2.7
1	0.14	0.12	11.9
1.2	0.21	0.23	16.2
1.5	0.45	0.58	Clipping

one in terms of fidelity—the passive split RIAA. The real drawback of this topology is the S/N ratio, because the equalization is done in a totally passive way, so it is necessary to have a very high amplification factor in order to loose it with further attenuation. The RIAA equalization network requires three time constants: 1) low-frequency attenuation at 3.18ms; 2) low-frequency emphasis at 318µs; 3) high-frequency attenuation at 75µs.

In the split RIAA topology these time constants are separated between two gain stages and implemented using two equalization networks, one after the first active stage and the other after the second. In my implementation the first network implements the first two time constants, while the second network implements the third one. In addition, this circuit introduces a subsonic filtering by means of two RC decoupling networks that isolate each stage. This filtering—even if not mandatory in RIAA standard—is preferable to decouple low-frequency signal fluctuations coming from the pickup.

When the circuit topology is defined (fixing the position of the two filters), you just need to find the value of the RC components in order to have the proper equalization curve. A first definition can be done using simplified formulas, but a fine-tuning requires simulation tools. The main problem is to find the right tubes and topology for the active stages.

A proper overall gain for MM pickups at 1kHz is normally in the range of 40dB. Considering an insertion loss of 20–25dB for the passive equalization, you need a total gain of 60–65dB.

In order to improve S/N ratio, the first stage must have the highest possible gain, still maintaining the capability to feed the following passive network. To do that, high gain tubes are mandatory, so the straightforward solution is the 12AX7 tube (the highest gain tube for audio I know). Basically you still have the possibility of using it in SE or SRPP configuration (as is well-known, the second one has the big advantage of dividing by two the output impedance of the stage, maintaining a very high gain), but in order to have a very compact stage, I used the first option (the gain is 36dB).

The situation for the second stage is even more critical: It must provide an acceptable total gain while driving a further stage with an input load in the range of 100kΩ (the highest potentiometer value normally acceptable for S/N reasons). Because these two requirements are in conflict, some designers are introducing a third stage for current buffer, solving the problem in this way. In order to avoid an additional stage, you must find a tube with a still high mu but a reasonable output impedance. There are some tubes suitable for this stage, but the only one available in my stock was the 12AT7, so my decision was very easy. Once again, you have the option of SE and SRPP configurations, but for the same reason above I chose the first one.

In this configuration the stage is providing a gain of 31dB. To have the highest gain, both the cathode resistors are bypassed with capacitors. Because the first equalization network has a loss of 22dB and the second one of 4dB, the overall gain at 1kHz is 36 + 31 - 22.5 –4 = 40.5dB, just as expected. The maximum acceptance of the preamplifier is limited by the second stage polarized at -2V, thus it is corresponding to 400mV at 1kHz, while the minimum acceptance is in the range of 50mV at very low frequency. To get a reasonable precision on the RIAA curve implementation, you must implement all the stages with 1% resistors and the best capacitors you can find.

I suggest you buy more capacitors than needed and then select them (the simple capacitor measure included in most testers is sufficient). Many words have been spent about the sound of the capacitors, and this stage is really one of the points where you can highlight the differences of each cap's technology. I suggest you start using standard MKT and then, if you prefer, move to paper/oil and so on. To be honest, my amplifier is still running with the original MKT of the first shot, because I think they are in line with the general quality level of the amplifier. Also for S/N improvements, I migrate immediately to DC heating (the results with AC heating were totally unacceptable).

I also tried to put the heater at a low positive voltage; in this way the leakage electrons leaving the heater are rejected from the cathode (that is at ground potential) improving the S/N ratio. To be honest, I didn't try the two solutions in order to verify the real effect on the noise level. You will find the Microcap model of the phono stage on my website, www.tube-friends.com.

Microcap is a simulation program available in evaluation version for students. You can download it at www.spectrum-soft.com. Even with the limitations (in terms of maximum components) of the evaluation version, this program is suitable for most of the simulation that could be necessary in the design of tube-based amplifiers. The real limitation of this program is the number of existing models for tubes. In fact, while it is quite easy to build a simplified tube model using the "3/2 power low," it is more difficult to get SPICE models affordable in the saturation region or in positive grid driving.

On my website you will find the SPICE library of the simplified models for all the tubes I used in these designs (but for the pentode I just produce the triode model). For additional information on tube SPICE modeling, please refer to the very interesting article at www.birotechnology.com/articles/Vtspice.

Even with its limitations (considering that in phono stage the working point of the tubes is in full class A area), the simplified model is quite good and the simulation provides results perfectly comparable with the real circuit.

THE POWER SUPPLY

In order to contain system costs and dimensions, I used silicon diodes and RC cell filtering for the power supply design. The power supply features two main sections, with a modular approach. In the first section there are the anode voltages for the two final stages (V1A and V1B), the anode voltages for the driver invert stage (V2 and V3), and the negative voltage for the final stage polarization and active load (V7). I implemented this section using two secondary windings of a custom 250VA main transformer. One winding derives both Va1 and Va2 (with two independent outputs of the winding). Another secondary winding is used for Vd.

We can also include in this section the heater supplies for the PL504 and 12AU7 for the active load. They are provided by two 12.6V sections of the main transformer connected in series with the center tap grounded (**Fig. 4**).

For the UCL82 I added a dedicated transformer (TR3). Because 54V is not a usual value, I used a 48V transformer with more power, in order to have a higher secondary voltage with a more limited load (because normally the nominal voltage value is granted at full power). If you replace the UCL82 with PCL82 or ECL82, you must also change the transformer. All these heaters are powered in AC.

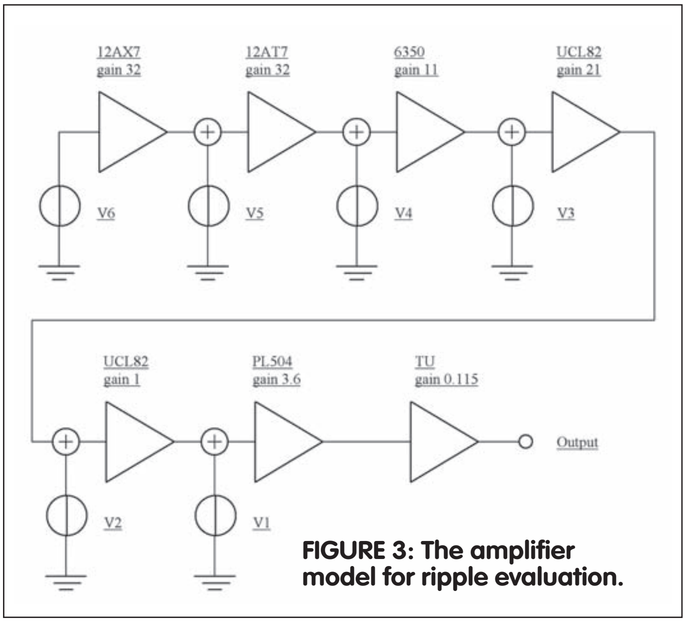


FIGURE 3: The amplifier model for ripple evaluation.

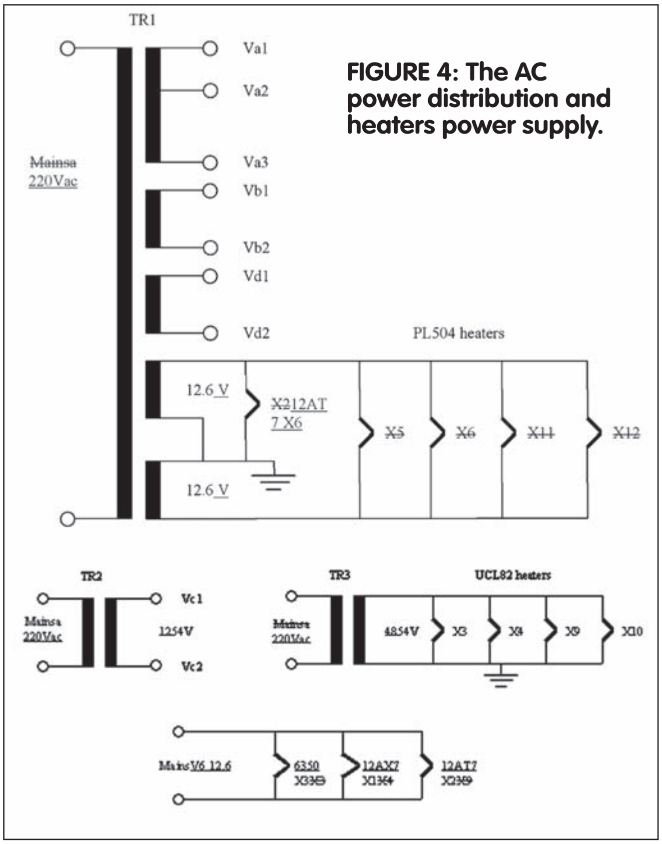


FIGURE 4: The AC power distribution and heaters power supply.

The second section of the power supply includes all the anode voltages for the preamplifier and the phono stage. They are derived from a single section of the custom transformer (Vb). The preamplifier heater power supply is provided by a dedicated transformer (TR2).

In this case I used a standard 12V transformer with a little higher power in order to get 12.6 DC voltage after the filtering. I recommend you use a dedicated transformer anyway, in order to reduce parasitic coupling between the heaters of the pre section and the other sections of the main transformer. With a different transformer, you can arrange the resistors R12 and R13 in order to get the proper voltage value after filtering.

My design, based on a 220V 50Hz mains, is optimized for the 230V level, since this is the normal value available in an Italian house. For the design of the RC filters I used the PSU program that you can download at www.duncanamps.com/psud2/. This program provides good results, but a fine-tuning with the real components is necessary.

The simulated ripple voltages are quite precise, assuming that you know the ESR of the capacitor you are going to use. But I did not, because normally I buy them from surplus and cannot get their complete documentation easily. The schematics include the winding resistance, so you can easily adapt the power supply to different transformers.

To design the power filtering I used a simplified model of the amplifier illustrated in **Fig. 3**. In the model each power-supply ripple is considered a voltage generator in the amplification chain. The noise contribution on the load for one ripple generator depends on the number of following amplification stages. To simplify, I considered the total noise as a sum of each contribution. So if you fix an acceptable ripple level on the load, you can define the maximum ripple level for each stage by the model.

Furthermore, for the push-pull section of the amplifier (from Smith inverter to final PL504 push-pull), you must consider the harmonic cancellation effect in the stages that increase the CMRR, so the ripple requirements for this section are more relaxed. I measured a ripple attenuation factor around 100 in these two stages. For the previous stages in single-ended configuration, this discount is no more applicable and the ripple requirements become stronger at each stage.

The measured results compare well with the estimated ones, as far as the PP section is concerned. The actual noise of the SE section is more influenced by the layout and parasitic coupling effects, so the result can be very bad in an inappropriate layout implementation. I can say that the PP section is quite easy to be realized while, considering the noise problems I encountered with the 6350 tube and the pre-phono stage, I can recommend the implementation of these two sections only to expert DIYers. I fixed as design target a ripple level of 1mV RMS, corresponding to 81dB of S/N, which is normally an acceptable value.

For the power supply 5% resistors are acceptable. Using different transformers, you would need to fine-tune some resistors in order to obtain the indicated voltage values with a reasonable error (1–2%).

THE ASSEMBLY

I followed a modular approach in assembling the amplifier. On one PC board with a metal plane (4″ × 8″, more or less), I assembled the driver inverter section (five noval tubes), while, to increase mechanical strength, I directly assembled the final stage on an aluminum plate with the same dimensions (four magnonoval tubes). The four trimmers for plate current tuning are soldered on a small PC board—it must be easily accessible when the circuit is assembled.

The power-supply filters are installed in two PC boards (4″ × 6″, more or less), with the exception of the pre-phono filtering section, which is directly assembled on another PC board with the same dimensions, hosting also the active section (three noval tubes). I used gold-plated ceramic sockets, and I recommend the shielded socket for the 12AX7 of the pre-phono. Vibration dumpers are generally not necessary, apart from the 6350 tube, where they are really mandatory.

For all the active sections, even using PC boards, I realized a 3D assembly by means of contact strips directly screwed on the PCB. The metal plane of the PCB is used as diffused ground plane.

I first installed all these circuits on an experimental wood base (**Photo 2**), but later transferred them to a metal box, which I had originally designed for another amplifier (**Photo 3**). This box is a combination of an iron structure with black deposition on surface and wood panels for aesthetic purposes and is divided into two totally shielded sections. In the rear section the two output transformers are installed one on top of the other.

This box provides both electrical and magnetic shielding. In the front section of the box all the power transformers and circuits are installed in the lower part, while on top a metal plate sustains the active circuits. In this way the tubes (apart from the phono section that is mounted internally) are visible from the outside through a big window in the front plate (**Photo 4**).

A totally drilled top metal cover is

PHOTO 3: The mechanical kit.

PHOTO 4: The final look—tubes.

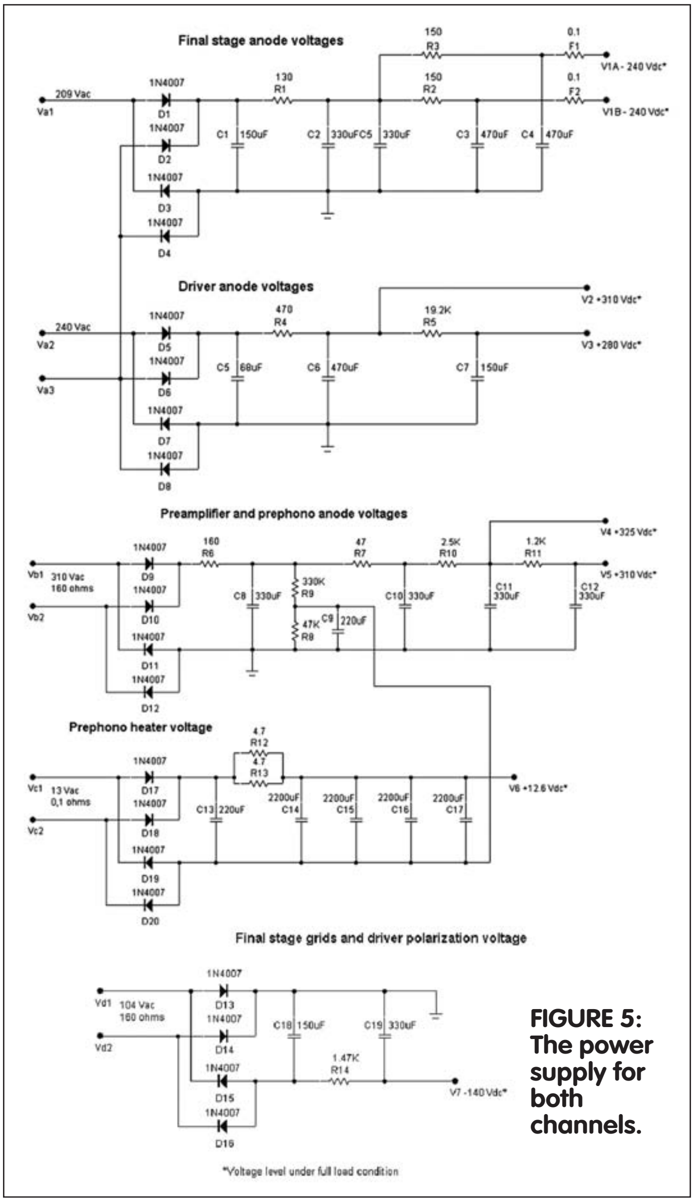


FIGURE 5: The power supply for both channels.

PHOTO 5: The final look—front view.

completely shielding the tubes section, providing a suitable air flow to refresh them. All the connections are on the rear, directly screwed on the metal structure (**Photo 6**). The system is completed with a wood base and a wood front panel. I also designed special knobs (one for volume and one for source selection) and feet (three of which are screwed on the wood base) in brass (**Photo 5**).

THE TUNING AND OVERALL PERFORMANCES

For the active circuit it is preferable to use 1% resistors. Sometimes the required value can be achieved by combining (series or parallel) two resistors.

The circuit requires three different types of tuning. Due to the DC coupling, the inverter driver section is sensitive to power-supply values (V2, V3, V8, in **Fig. 1**). In order to ensure the class A polarization for the first section of the PCL82 tubes, you must adjust R17 (one channel) for +1.5V at the cathodes of X4_1 and X5_1. With the voltage levels of the schematics, R17 of 100kΩ is providing exactly 1.5V in my circuit. Pay attention that a voltage value higher than 1.5V—even if it is interesting in order to avoid class A2 operation for the X4_1 and X5_1—will move the polarization of the following X4_2 and X5_2 tubes, resulting in an unacceptable reduction in the circuit dynamic.

The second tuning is necessary to fix the plate currents and cancel the DC components in the output stage. The cancellation of the DC component is mandatory to avoid premature saturation in the output transformer. Even if a normally good output transformer can tolerate a small DC component, it must be reduced to a minimum (because it is impossible to guarantee a perfect balance over time). You must use the trimmers R34 and R36 (one channel) to do this.

PHOTO 6: The final look—rear view.

I suggest you start switching on the amplifier without the PL504 tubes and tune the trimmers for around -42/-45V at the grids. Then insert the tubes and, finally, control the total plate + grid current by measuring the voltage drop across the resistors R28 and R31. Due to the high value of the capacitors C11 and C12, the voltage will change very slowly when you move the trimmers, so the procedure will require attention in order to avoid a long trial-and-error sequence. For an 80mA current you must measure 16mV on 0.2Ω resistors. As usual, do the tuning after at least 15 minutes from power on and repeat after 10–20 hours of work.

I also added a third tuning circuit for the AC balance and will explain why. In **Fig. 6** you can see the output spectrum measured on an 8Ω resistive load with a pure 1kHz tone generating an output power of 8W. Without any AC compensation the second and third harmonics are comparable. After compensation, you can reduce the second harmonic by at least 12dB (right channel), producing a benefit on the total harmonic distortion (**Fig. 7**).

But I must emphasize that while the AC compensation reduces the THD figure thanks to the even harmonics cancellation (0.4% at 5W is very good for an amplifier without global feedback), its effects are not totally predictable. What is really important is the effect on the sound.

With some music types the uncompensated version looks to me more natural than the other one. In order to apply AC compensation you need a spectrum analyzer (a PC audio board plus adequate SW is fine) or a selective voltmeter (I used a voltmeter tuned on the second harmonic). Trimmer R40 (one channel) must be rotated in order to minimize the second harmonic or THD (because odd harmonics are unaffected, it is almost the same).

The –3dB bandwidth at 10W is ranging from a few Hertz (–0.4dB at 20Hz) to 19kHz (–3.5dB at 20kHz). The noise level (with line input in cc) is around 700µV, corresponding to a S/N value around 85dB.

CIRCUIT DRAWBACKS

Due to the problems I encountered designing and testing Tuono, I must mention two possible improvements for the circuit. First of all, the high value capacitors in the coupling of the driver stage with the final stage require a relatively long period to be charged at power-on (some seconds). The result is an overcurrent pick on the final tubes that could affect their life, so a power-on delay circuit on V1 voltage of 30 seconds could be a good improvement.

Furthermore, the grid polarization of X3 through the volume potentiometer could pick up a lot of noise in a critical layout. In this case a second resistor of

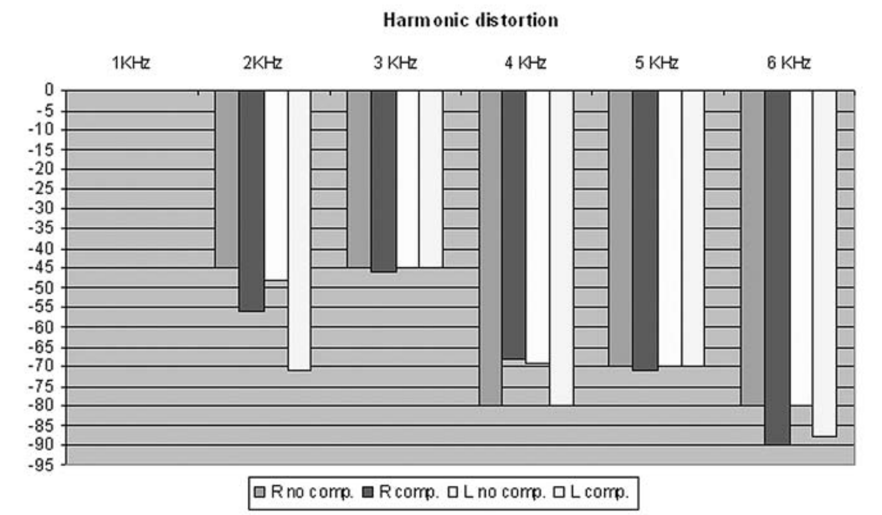


FIGURE 6: The output harmonics with and without AC compensation.

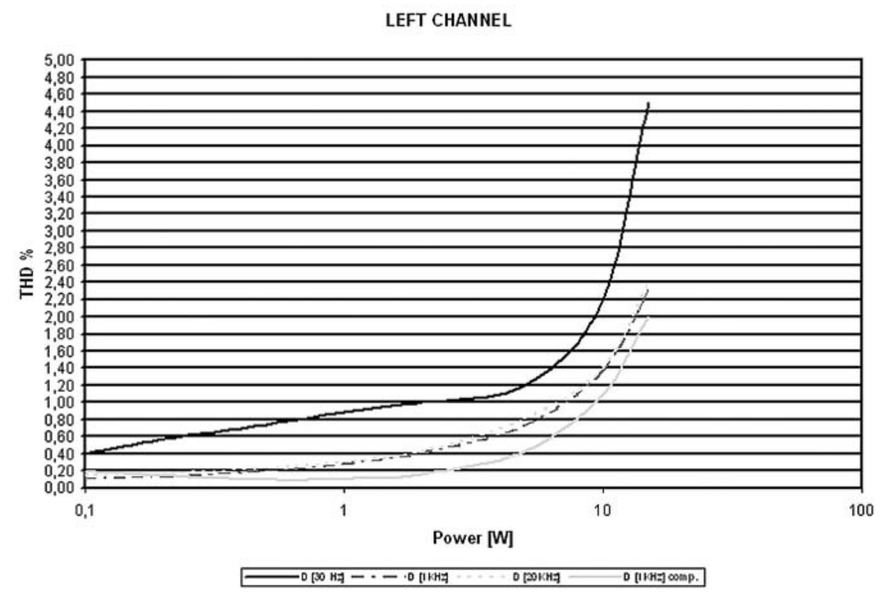


FIGURE 7: The output THD+N vs. output power.

AMPLIFIER PARTS LIST—ONE CHANNEL.

Reference	Value	Power	Voltage
R1, R14, R18	45k	½W	
R2	970	½W	
R3	224k	1W	
R4	244k	½W	
R5	28.5k	½W	
R6	970	5W	
R7	820k	½W	
R8	22k	5W	
R9	390	½W	
R10	47k	½W	
R11	Potentiometer 2x100k Alps Blu series		
R12	550	½W	
R13	23.5k	5W	
R15	200k	½W	
R16, R19	200k	1W	
R17	100k	½W	
R20	75	½W	
R21, R24	484k	½W	
R22, R26	220	½W	
R29, R32	220	2W	
R23, R25	11k	10W	
R27, R30	10	½W	
R28, R31	0.2	½W	
R33, R35	10k	1W	
R34, R36	Trimmer 10k	1W	
R37, R38	22k	½W	
R39	6.8k	2W	
R40	Trimmer 100k	1W	
C1	150µF		400V
C2	330µF		400V
C3, C7	220µF		35V
C4	10nF		800V
C5, C8	2.2nF		800V
C6	22nF		800V
C9	0.33µF		400V
C10	0.68µF		400V
C11, C12	150µF		250V
C13, C14	2.2µF		250V
X1	½ 12AX7		
X2, X6	½ 12AT7		
X3	½ 6350		
X4, X5	UCL82		
X7, X8	PL504		
K1	See text		
F1, F2	200mA fuses		

high value very close to the X3 grid will reduce the effect. Be careful that this doesn't change the phono stage gain and equalization; otherwise, a redesign of the network could be necessary.

POWER SUPPLY PART LIST—BOTH CHANNELS.

Reference	Value	Power	Voltage
R1	130	10W	
R2, R3	150	10W	
R4	470	5W	
R5	14K	2W	
R6	160	5W	
R7	47	2W	
R8	47K	½W	
R9	330K	2W	
R10	2.5K	5W	
R11	1.2K	2W	
R12, R13	4.7	5W	
R14	1.47K	2W	
D1-D20	1N4007		
C1, C7, C18	150µF		400V
C2, C5, C10, C11, C12, C19	330µF		400V
C8	330µF		450V
C3, C4, C6	470µF		400V
C9	220µF		100V
C13, C14, C15, C16, C17	2200µF		35V
TR1	220V	See *Fig. 5*	
TR2	220V/12V	See text	
TR3	220V/48V	See text	

HOW DOES IT SOUND?

As every DIYer knows, it is very difficult to be impartial when you spend more or less one year of your free time on a new design. I compared Tuono using my preferred music with my personal reference (a single-ended using 6C33 tubes). Due to the same technical approach, both amplifiers have the same correct extension in frequency (bass is deep and robust) and enough energy to follow all the transients of the classic orchestra. The sound stage is well-extended in width and height.

As in the major part of the tube-based amplifiers, you can have all the music details even at a very low sound pressure: In a normal room with medium sensitivity loudspeakers, you will never look for more power. Tuono is just losing a little definition compared to SE configuration. On the other hand, with guitar and voices, Tuono is providing its best, it sounds for sure different and, at a first listening, better than the SE. Furthermore, AC compensation can introduce a degree of freedom by better characterizing the "push-pull like" sound.

Claudio Rosada *is an electronic engineer with major experience in digital circuits. He spent ten years designing telecommunication equipment and from 1998 has been working in the automotive electronics field. He "discovered" tube-based electronics a few years ago to improve his personal hi-fi equipment. Now he is active with a group of friends in designing and comparing different tube-based amplifiers and preamplifiers. His preferred music is pop/rock from the '70s and '80s and full-orchestra classical. He often uses songs with voice and acoustic guitar as well as symphonies with high dynamics for accurate comparative test sessions. Claudio can be contacted at* claudio@tube-friends.com.

REFERENCES

1. Kelly, Mark. "The Search for Linearity," *Glass Audio* 6/96.

2. Chiomenti, Luca. "Una valvola al mese," *Costruire Hi Fi* 29, July/Aug. 1997.