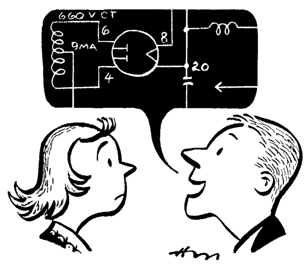
Audio Classroom

Practical Audio Design Part 2: Power-Supply Filters

BY JOSEPH MARSHALL



This article (reprinted from Audiocraft, *February 1956) on power-supply filters is the second in our new* GA *series entitled Audio Classroom. We'll be publishing a collection of reprints—mostly from the 1950s—focusing on the basics to help you better understand tube design.*

In Part 1 of this article we considered at some length the selection, application, and modification of power transformers. Choosing a suitable rectifier is ordinarily not much of a problem. The principal considerations are: 1) ability to handle the desired voltage and current; 2) space occupied; and 3) heating. Cost is usually not a factor because the smallest rectifiers cost very little less than the largest. In compact construction space saving may be important, and bantam or miniature rectifiers may be preferred. If the equipment is to be totally enclosed, heating may be a consideration, and rectifiers with lower filament current may be preferred to reduce heat.

As noted before, the essential data for choosing a rectifier are presented in charts and curves of the tube manuals. Three charts are usually given. The first is a simple rating chart which tells at a glance the maximum parameters under which the tube will operate satisfactorily. In *Figs. 1* and *2*, the maximum rating charts for the 6AX5-GT and the 5U4-GB are presented. Please note, to begin with, that the boundary lines of operation for capacitor-input filters are not linear, but have two angles like a mansard roof; the curve is horizontal up to a point, then begins to slope at one angle, and finally, after a critical point, it slopes again at a much sharper angle.

In the case of the 6AX5-GT this occurs at 350V per plate AC input. The tube will deliver 75mA per plate with 58V AC per plate, and 62.5mA with 350V per plate; but, if the voltage is raised beyond 350, the permissible current drops rapidly until at 450V AC per plate only 40mA can be drawn. On the other hand, 450 is the critical voltage for the 5U4-GB. At that point it can deliver 137.5mA per plate, but only 81mA per plate at 550V AC input, which is the maximum rated input voltage. It is quite simple with these maximum rating charts to determine what tubes can do the job at hand.

The second and third sets of curves give various practical operating parameters with capacitor and choke inputs; from these, the exact performance can be determined for any given set of oper-

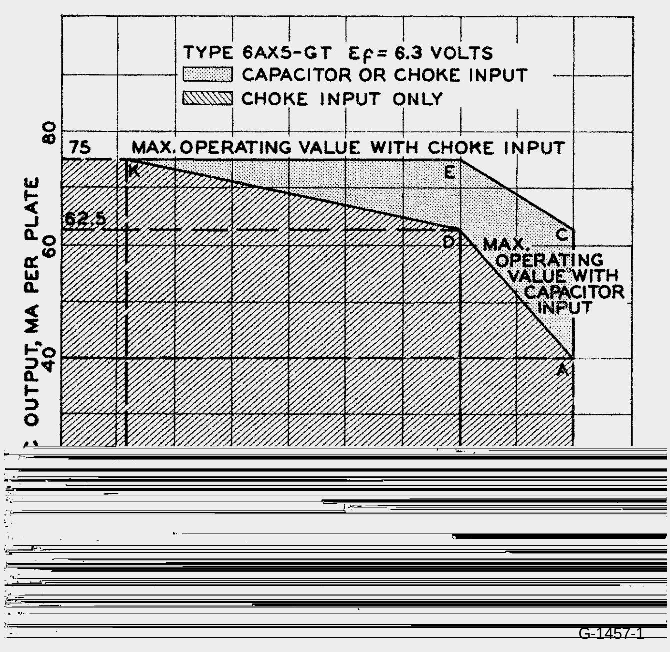


FIGURE 1: A rating chart for the 6AX5-GT.

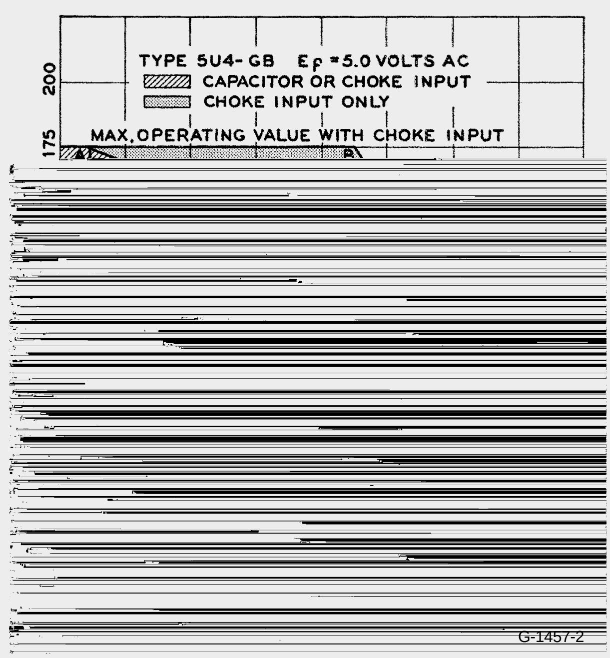


FIGURE 2: Maximum ratings for the 5U4-GB.

ating conditions. Capacitor-input curves (*Fig. 3A*) require no explanation.

CHOKE-INPUT FILTERS

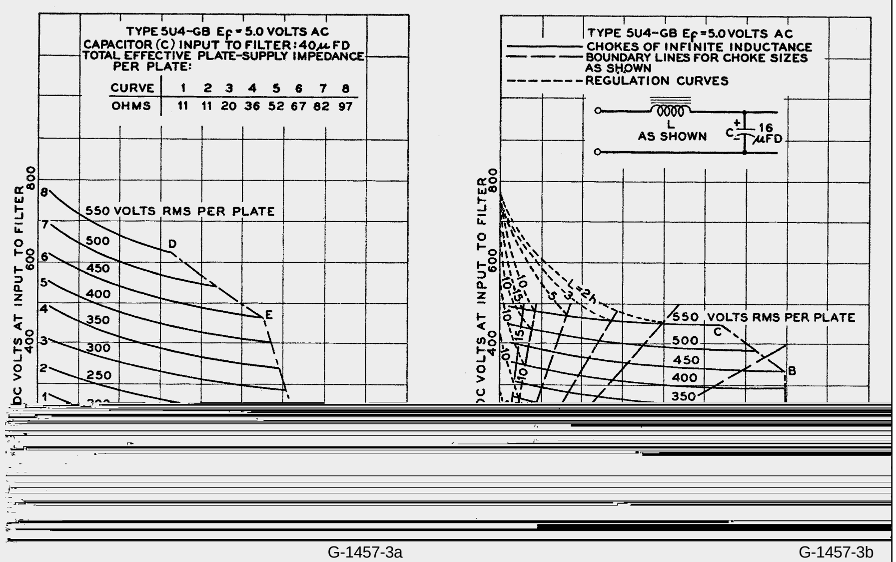
Choke-input curves (*Fig. 3B*) are somewhat more complicated in appearance, but are really just as simple to apply once a few things are clear. The inductance of a choke varies with the current through it, and falls very sharply when the current is high enough to saturate the core. There is, therefore, a *critical* inductance for any load; when the load changes, as it invariably does in equipment using choke-input power supplies, it is essential that the choke have critical inductance or more at both the maximum and minimum loads. If it does not, the reactance of the choke will be so low at some point in the operating range that it has very little or no effect—the rectifier will then appear to face the capacitor which follows the choke, and will behave as if the filter were a capacitor-input type. There will be a violent rise of voltage, and the regulation would be no better (and possibly worse) than if a capacitor-input filter *were* used.

The formula for critical inductance is quite simple. First, determine the load resistance by dividing the voltage by the current (in amps) the supply is to deliver and, to be accurate, add the series resistance of the filter. If the supply is to deliver 400V at 100mA, and the choke resistance is 200Ω, the load resistance is 400/0.1 + 200 = 4,200Ω. However, if the current falls to 40mA, the load resistance rises to 400/.04 + 200 = 10,200Ω.

The critical inductance for a 120-cps full-wave circuit will be approximately

$$\frac{\text{Load resistance}}{1{,}000}.$$

In the example given, the critical inductance would be 4H at the full load and 10H at the minimum load. The *optimum* inductance is twice the critical inductance. So, for the above example, we would need a choke with an inductance at 40mA of 20H, and no less than 8H at the 100mA point.



FIGURES 3A and 3B: Operating characteristics for capacitor- and choke-input filters.

The newer type of graph for choke-input filters eliminates the need for these calculations, and makes it possible to determine the behavior of a given rectifier with a choke of a given inductance or to choose the optimum inductance at a glance.

It will be noted that *Fig. 3B* has, besides the familiar solid lines representing different AC input voltages, additional curves in broken lines. The long-dash lines radiating from the lower left corner are the load lines for different choke values. There is also a set of short-dash lines marked with values of inductance too, which meet and extend to the left the solid input-voltage lines; these show what happens to the output DC voltage with chokes of the given values when the current drops below certain points.

For example, the long-dash curve marked 2H and the short-dash curve also marked 2H intersect the 550V AC solid-line curve at the 200mA coordinate. This means that with an input of 550V AC per plate, and a load of 200mA, the 5U4-GB will deliver 450V DC into a choke of 2H. Now let's see what happens as the load is changed. If the current falls to 100mA we see, by following the short-dash line, that the DC voltage would rise to 550. An inductance of 2H is less than the critical value at this load and is, in effect, a short circuit; the rectifier now works into the following capacitor and the DC rises to the peak value of the AC; the regulation is poor and no better than it would be with capacitor input.

On the other hand, going the other way, we follow the solid line and see that we can maintain close to 450V DC output between 200–275mA, the maximum rating for the tube. Obviously, then, with a choke of 2H we must keep the current from falling below 200mA if we want the regulation to be good. To put it another way, a 2H choke is usable with this tube only when the minimum current does not fall much below 200mA.

The general rule when designing a choke-input power supply is to choose operating conditions (or choke size) so that the desired DC output voltage and current drawn will always fall *below and to the right* of the long-dash line representing a given inductance.

TUBE CHOICE

Although there are dozens of rectifier tubes, 99% of audio applications will be served with the following most common types:

For maximum loads above 175mA—5U4-GB or 5R4GY.

For maximum loads between 125–175mA—5V4G.

For maximum loads up to 125mA—5Y3-GT or 6AX5-GT.

For maximum loads up to 75mA—6X4 or 6X5-GT.

When the extreme rating of the smaller of two possible tubes is approached it may be advantageous to use the next larger tube. When 70mA is required, the maximum input for the 6X4 or 6X5-GT is 325V AC per plate, and the DC output would be 300V. But with the 5Y3-GT or 6AX5 the input could be raised to 450V per plate, and a higher output voltage could be obtained; or, with the same 325V per plate input, the 5Y3-GT could deliver 350V DC output.

Sometimes space is a consideration, and the miniature 6X4 would be preferred even with lower output voltage. Occasionally there is only a 6.3V filament winding on the power transformer, and in such cases the 6V series of rectifiers with cathodes must be used. Moreover, the use of a rectifier with an independent cathode prevents excess voltages from appearing across the filter capacitors during warm-up and it is then possible, if necessary, to use filter capacitors of more compact form and lower voltage rating.

It may be necessary or advisable in rare cases to increase current capacity by operating two rectifiers in parallel. There is some difference of opinion as to whether the two sections of a single rectifier should be paralleled or corresponding sections of two rectifiers. I prefer paralleling the two sections of one rectifier, because when one tube goes out the power supply will still operate (as a half-wave supply). But there isn't much choice because, in either case, the remaining tube will be seriously overloaded and may be damaged.

Because of differences between individual tubes or sections of tubes, there will not be an equal division of the load with parallel operation. This can be corrected at least partially by connecting a resistance of 50–100Ω in series with each plate. Of course, if the resistors are not reasonably matched there may be no improvement at all, so they should be paired with an ohmmeter for the best possible match.

It is much more preferable to parallel identical tubes—but it *is* possible to use dissimilar tubes. Some TV sets, for example, use one 5U4-GB and one 5Y3-GT; one section of the 5U4 is paralleled with one section of the 5Y3. There is little to be gained from the use of dissimilar tubes, however, and their use may cause severe trouble in case of breakdown.

HUM FILTERING—GENERAL

The principle behind hum filtering is a rather simple one. At the output of the rectifier the current has two components: the desired DC component, and the unwanted AC component (or ripple). If we could devise a network that would let the DC through, but close the door on the AC, we could take the one and leave the other behind. We need something that, when placed in series with the load, would offer very little resistance to DC, but a high resistance (or, more accurately, reactance) to AC. This would provide the closed door or dam for the AC.

Now, if we added another element from the rectifier output to ground that offered a very high resistance to DC but a very low reactance to AC, the dammed-up AC would be bypassed to ground. In *Fig. 4A*, the element A has high resistance to AC but low resistance to DC; the element B has high resistance to DC but low reactance to AC. When they are given a choice of paths, all electrical currents divide in inverse proportion to the resistance (or reactance) offered by the several paths. They take the easiest way, and the path of least resistance (or reactance) will carry the higher load.

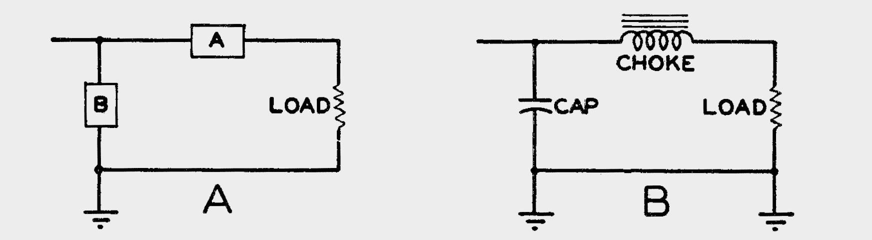


FIGURE 4: Power-supply filters (see text). G-1457-4

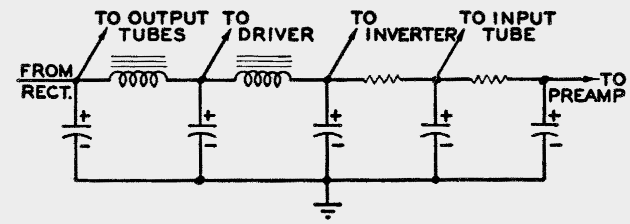


FIGURE 5: The progressive filter design. G-1457-6

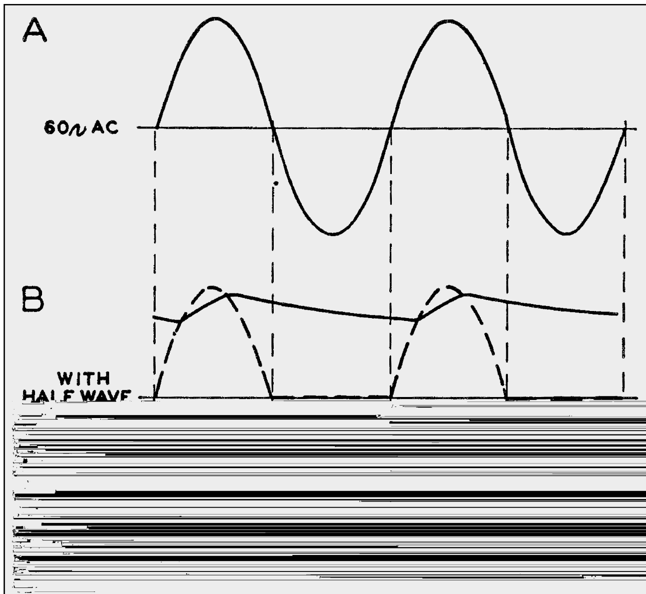


FIGURE 6: Full-wave ripple is at 120 cps. G-1457-7

An inductance has high reactance to AC but low resistance to DC, and so is suitable for the series element A. On the other hand, a capacitance has low reactance to AC but high resistance to DC, which are characteristics desired for the shunt element B. Working into such a crossroads most of the DC will take the easier road provided by the inductance, while most of the AC will take the easier road provided by the capacitance. At the output of the inductance (*Fig. 4B*), a current is obtained which is very much freer of AC than at the input.

Single-section filters often suffice when the power supply feeds a power amplifier. For low-level stages with high gain, though, the residual ripple would be amplified and would be audible at the output. Additional filter sections are therefore added to reduce ripple even further. And to reduce the need for large chokes, the filter can be made *progressive*; that is, the different stages in an amplifier are fed from different points in the filter—the high-level stages close to the rectifier, the low-level stages far from it.

With such an arrangement (*Fig. 5*), only the first element of the filter has to carry the total current of the amplifier. The first choke might have to be capable of carrying 150mA, but the second choke would probably carry no more than 50mA and could accordingly be much smaller and less expensive. High-fidelity amplifiers may have as many as eight sections of filter. Besides reduction of hum ripple, the additional sections also provide decoupling (more on that later) and so perform two functions simultaneously.

COMMON SENSE

There are all sorts of complicated formulas for working out filters of any desired type or effectiveness. These are useful in special applications, such as figuring out the cheapest way to obtain filtering of a

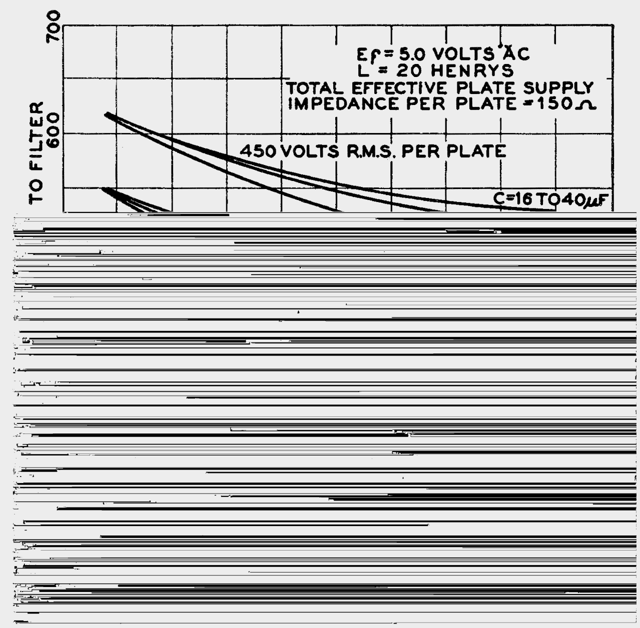


FIGURE 7: Capacitor-input curves for 5T4.

high-voltage supply for transmitters, or in a production amplifier. But for 99% of home audio applications, common sense in applying the information supplied by the tube manuals will be perfectly adequate.

A few points only need be kept in mind. First, the frequency of the ripple will depend on the type of rectification. A half-wave rectifier produces a 60-cps [The measurement for the unit of frequency we use today is Hertz. 1 Hertz = 1 cycle per second.—Eds.] ripple (we assume 60-cps line current in all cases) but a full-wave rectifier produces 120-cps ripple (*Fig. 6*). Here A is the unrectified AC input to the power supply. B is the waveform of a half-wave rectifier working into a capacitor load, which smooths the output by charging on peaks and discharging in the nulls. The saw-tooth wave representing the ripple is of the same frequency as the original 60-cps AC.

With a full-wave rectifier, however, the spaces between the positive peaks are filled by the inverted output of the second rectifier section, and the resulting waveform appears as in C. Here there are twice as many positive peaks, twice as many saw-tooth peaks, and accordingly the ripple frequency is 120 cps. It takes roughly twice as much inductance and capacitance with a half-wave supply to obtain filtering equivalent to that with a full-wave supply. It is easier and cheaper, therefore, to filter full-wave than half-wave rectifier supplies.

There is one exception. In low-fidelity equipment (such as table radios and small phonographs) the response is sloped sharply below 100 cycles, partly because the speaker baffling is limited, partly because a small and cheap output transformer is used, and partly because rolling off response below 100 cycles minimizes the danger of motorboating and other types of instability. It is then advantageous to use a half-wave supply for this reason: the slope in the response of the equipment will *itself* reduce the 60-cps hum, but it would have very little if any effect on 120-cps hum. In such a case the half-wave supply would require much less filtering than the full-wave, and the same hum level in the output of the radio could well be achieved at lower cost with a half-wave supply.

CAPACITOR-INPUT DESIGN

It has been noted that a capacitor-input filter produces highest DC voltage with a given AC input to the rectifier, and so is preferred whenever the current load is reasonably stable. The value of capacitance into which the rectifier works can be important. Up to a point, the higher the capacitance, the higher the DC output voltage. *Figure 7*, for instance, is the graph for the 5T4 rectifier. You will note that raising the capacitance from 4 to 16µF produces an appreciable rise in voltage, but there is little additional increase as the capacitance is increased beyond 16µF. Also, larger input capacitors give better filtering action.

On the other hand, a large capacitance may increase the *peak* initial charging current of the power supply beyond the rectifier's ratings and cause trouble. This is a consideration only when the power supply is expected to deliver close to the maximum possible current for the given rectifier. In such cases, it is wise not to exceed the maximum input capacitance specified in the tube manual. And when trouble is anticipated, it can be minimized by inserting current-limiting resistors of about 50Ω in series with the rectifier plates, as discussed previously.

In a capacitor-input filter the capacitor closest to the rectifier carries the greatest part of the AC current. The ability of a capacitor to carry high AC currents depends on its capacitance, voltage rating, and type of dielectric. The higher the capacitance and/or voltage rating, the higher the permissible AC current. Plain-foil electrolytics can carry higher ripple currents than etched-foil units, and paper capacitors can carry a much higher current than electrolytics. For most audio uses it will suffice to use the following rule of thumb:

Etched-foil electrolytics can be used for loads up to 70mA (DC) with no precautions whatever.

Plain-foil electrolytics can be used for DC loads up to 150mA with no precautions.

When the load exceeds 150mA, the best capacitors available with the highest working voltage and capacitances up to 40µF should be used.

If the current is much in excess of 150mA and the greatest insurance against breakdown is desired, it may be wise to use two capacitors in parallel; they will divide the ripple current and each will carry only a portion of the total. When the current load exceeds 200mA, the use of paper capacitors is worthwhile.

As in the case of power transformers, the rigid ratings are often disregarded in commercial practice today. Thus in TV receivers, the input capacitor as often as not carries ripple currents up to 100% greater than JAN ratings. Many of these operate for long periods without trouble.

Electrolytic capacitors invariably conduct some appreciable DC current because the dielectric is imperfect. This DC leakage may be fairly high with high capacitance. It is wise to make sure that the leakage of the input capacitor is not excessive, by measuring the DC resistance *after* a period of use. Electrolytic capacitors must be formed by applying a DC load for a period of time; when first installed, they usually have high leakage, which is greatly reduced when the electrolyte is formed—*if* everything goes right.

When the power supply is called upon to deliver more than 400V or so, the working voltage comes uncomfortably close to the maximum ratings of electrolytic capacitors. When the highest reliability is desired the capacitors can be used in series. The individual sections should each be shunted with a high resistance (*Fig. 8*) to equalize the load.

Aside from these considerations, capacitance of the filter capacitors is not very critical. In general, the higher the capacitance, the better the filtering; for audio amplifiers the individual sections should be at least 20μF and preferably 40μF. When making audio equipment for myself I use an 8 or 10μF paper unit for the input capacitor. This provides the highest insurance at the most critical point. I follow this with multiple-section or plug-in electrolytics of the highest practical capacitance and working voltage.

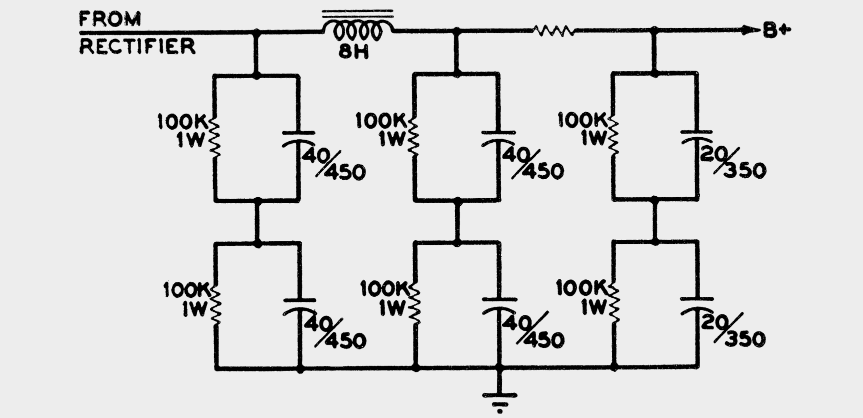


FIGURE 8: Filter for a high-voltage supply.

LIMITATIONS

The inductance of the choke used in a capacitor-input filter is, to be sure, important; but the choice is limited to what is available. Transformer companies have standard designs that offer a good compromise of various characteristics. Actually, in choosing a choke from a catalog the principal consideration will be the current-carrying capacity. There is some choice of inductance for a given current capacity, but not much, and the cost of a choke goes up drastically as the inductance or the current capacity increases.

Furthermore, the DC resistance also increases with the inductance, and the drop in output voltage because of the greater resistance may be more important than the improvement in filtering efficiency. It is cheaper to increase capacitance than inductance, and it is not very material (in a capacitor-input filter) whether a larger LC product is achieved with higher inductance or higher capacitance. An inductance of 8H or more is desirable in a power amplifier, and 8H chokes are available for just about any current load up to 300mA.

If you can afford it, it is nice to operate a choke well under its maximum rating—that is, to use a 200mA choke for a load of only 125mA. But, with the intermittent operation common for most audio equipment outside radio and recording studios, choke heating is practically never much of a consideration. There is no great disadvantage in operating chokes at their maximum ratings, nor much to be gained from operating at lower loads. However, exceeding the rating is another matter entirely because the inductance then drops severely and filtering action is greatly impaired.

Small chokes capable of handling between 50–100mA were very common in pre-war radios, especially console models, and can be salvaged from them. Occasionally the deluxe console models will yield chokes of 120–150mA rating, and even larger ones can sometimes be found in old public-address amplifiers. Size and weight give a rough indication of current-carrying capacity.

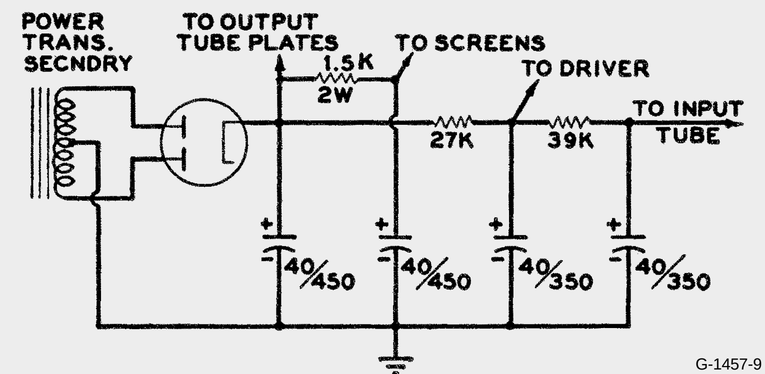


FIGURE 9: A chokeless power-supply filter.

If they have been stored in basements or garages under poor humidity conditions, corrosion may have opened the soldered joints where the ends of the windings are connected to the leads. It is often possible to repair these by slitting open the paper cover over the windings to expose the connections, and resoldering them or installing new leads. Not all experimenters are aware that old output transformers can be used as chokes in applications calling for currents of 50mA or less. One or two old output transformers and a three-section 40μF capacitor can make an excellent filter for a preamplifier, control unit, or similar equipment. When using a transformer this way the primary is used for the choke; the secondary is left open.

Many fine high-fidelity amplifiers today are powered by supplies using no choke at all. In these the voltage for the output tubes is taken directly from the output of the rectifier. This is possible because several conditions are met. First, the inductance of hi-fi output transformer primaries often exceeds 50H. This inductance presents a very high reactance to the AC ripple and behaves as if it were a big choke, because the output stages of high fidelity amplifiers are push-pull and almost always have means for balancing the output tubes quite exactly.

When the output stage is exactly balanced the hum in the output transformer will cancel out because it is in phase in both halves. Under these circumstances the hum suppression is high enough to be completely satisfactory. This expedient, however, does not work nearly as well with ordinary low-inductance output transformers and output stages which do not have provisions for balancing the two sections. *Figure 9* is a diagram of a chokeless power supply suitable for such amplifiers.

RC FILTER DESIGN

Resistance-capacitance (RC) filters are quite practical also for control units, preamplifiers, mixers, and such units wherein the current load is moderate. A real economy is possible by using a power transformer capable of delivering an excess voltage and then using relatively high resistors and capacitors in the filter. For example, if 300V at 50mA is needed we can design an inexpensive RC progressive filter much more compact than one using one or more chokes.

The only critical resistor is the first one, because it carries the total current. We can estimate the total current with the aid of the tube manual, or by the rule of thumb allowing 10mA for each low-mu triode and 2mA for each high-mu triode or pentode. We can use a transformer and rectifier chosen to deliver 400V at the input capacitor. We now have 100V we can throw away. The maximum resistance for the first resistor can be figured by dividing the desired or permissible voltage drop by the total current that will pass through the resistor. In the example this would be 100V divided by 0.05A (50mA) which gives us 2,000Ω.

Large capacitors must be used; 40µF would be suitable. I find it convenient to use an adjustable power resistor of 10W with a resistance about 50% higher than that calculated. The slider can then be moved to provide the required voltage at the first take-off point. Additional filtering is obtained from the decoupling network which follows, as we shall discuss later.

There is a useful trick for reducing ripple with RC (and one-choke) filters (*Fig. 10*). You will see that a resistor is connected from the input of the filter to a point following the second section. This is a form of feed-through. The ripple is out of phase at the two points and, if the feed-through ripple is equal to the ripple existing at the point to which it is applied, cancellation occurs.

The value of the feed-through resistor is roughly ten times the value of the two resistors in series (or, if a choke is included, the sum of the reactance of the choke and the resistance of the resistor). Cancellation can be adjusted either by making the feed-through resistor a rheostat or by adding a small pot at the end of the filter and adjusting it for a null in hum. This method can produce complete suppression of the fundamental ripple frequency; it is not as effective on the harmonics, but in most cases the harmonic ripple is no worse and usually a little better than that without feed-through.

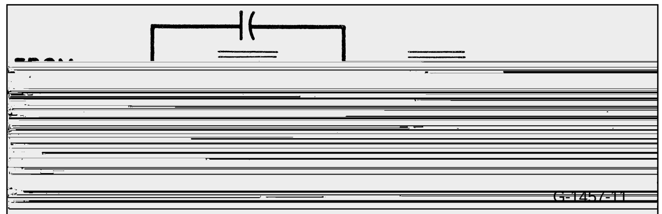


FIGURE 11: Tuning a choke to reduce ripple.

CHOKE-INPUT DESIGN

It has been emphasized that the design of a choke-input filter is complicated and critical and that, unless you're very careful, it is easy to run into trouble. Fortunately, there is very little application in audio today for choke-input filters; the introduction of the 5U4-GB with its higher current capacity and lower internal resistance has removed most of the marginal needs for choke input. A few comments, however, will not be amiss in this elementary treatment.

A choke-input filter is desirable only when the current swing is very wide and the regulation must be very good. A Class-B power amplifier of very high output (100W or more) is just about the only audio device that poses such a problem. I mentioned above that the 5U4-GB tube had eliminated the need for marginal applications. Consider, for example, the case of a Class-AB2 amplifier using a pair of 6L6s or KT66s with fixed bias for an output of 50W.

Plate voltage can be 375–510V, and the current swing (of the output tubes only) will be from 80mA with no input to 175mA with maximum input. If we use choke input and a 5U4-G we will need 550V AC per plate and we will get about 470V DC at the no-signal point and about 450 at the maximum-output point. This yields a swing of only 20V, which is very fine regulation indeed. But let us see just how much improvement, if any, this fine regulation offers over that possible with capacitor input.

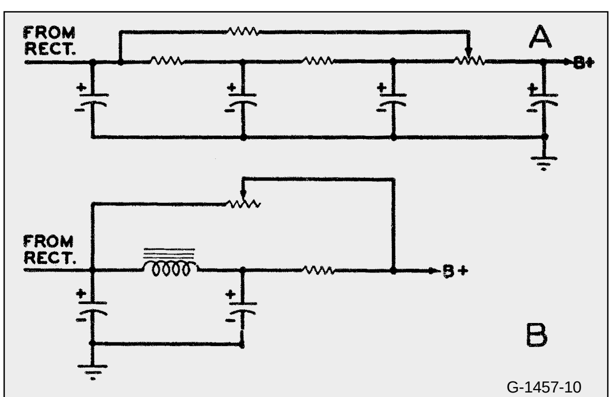


FIGURE 10: Feed-through hum cancellation.

With a capacitor-input filter the 5U4-G could deliver 510V at the zero-signal point and about 425 at the full-output point, with an input of only 425V AC per plate. Assuming an efficiency of roughly 60%, the amplifier would deliver about 47W with choke input and 44.5W with capacitor input. The 5U4-GB, however, reduces and in fact eliminates the disparity. With the same 425V per plate, it would deliver the same 510V DC at zero-signal point; but at the 175mA full-output point the voltage would be around or just under 470V, for an output of close to 50W. Clearly, the additional complications of choke input are not justified. In such operation it is very much more important to regulate the voltage to the screens, and this problem is very little (if any) worse with capacitor input.

The problem teeters in favor of choke input, however, when more than 50W are needed. First, the plate voltage needed will exceed 500V, and this surpasses the maximum ratings of most electrolytic capacitors. With bigger tubes, the current swing may exceed 125mA between no-signal and full-output conditions, so that here choke input may be worthwhile and possibly cheaper.

Recently added charts in the tube manuals greatly simplify the design of choke-input filters. The inductance of the input choke is the most important consideration. We have already seen that the inductance must be larger than a certain critical value at both the minimum and maximum load conditions; this rules out the ordinary choke when the current load is high. Ordinary chokes are designed to hold the inductance fairly constant with variations in load.

A choke which might have critical or optimum inductance at maximum load might easily have too little inductance at minimum load. To solve this problem many chokes are made with a large gap so that the inductance rises steeply as the current decreases. These are called swinging chokes, and are rated at two inductance values. For example, a 5–20H swinging choke would have a minimum inductance of 5H at the maximum rated current, and a minimum of 20H at about one-third the maximum current.

The need for a swinging choke is illustrated by the example just considered. You will note that to obtain about 450V at the zero-signal, 80mA load, a minimum inductance of 5H is needed. Suppose that we used a choke having only 3H at that load. Then we would get about 450V at the 175mA maximum-output point, but at the zero-signal point the voltage would rise to more than 510V. This would give us no better regulation than we could obtain with a capacitor-input filter, and there would be no point to using choke input since the same choke would work very well in a capacitor-input filter.

When designing a choke-input supply, therefore, the important thing is to choose a choke of sufficient inductance to keep the voltage from rising unduly at the minimum load point. The choke boundary lines on the graphs permit one to do this quite simply; it is only necessary to keep in mind that both the minimum- and maximum-load points must fall to the right of and below the dashed line for a given inductance. Or, conversely, choose a choke whose radial load line is always to the left of and above the operating point for minimum load. For example, if the minimum current does not fall below 200mA, you can get up to 450V DC at about 280mA with a 2H choke. But suppose you want 300V with a current swing ranging between 50mA (zero-signal) and 300mA (maximum output). You can obtain this from two 5U4-GBs with an input of about 400V AC per plate, but you will need a choke higher than 5H; otherwise the rise in voltage at the zero-signal point will be excessive.

It happens occasionally that the minimum load is lower than that permissible for a choke of a given inductance. You can fix things by terminating the filter with a bleeder resistor drawing enough current to raise the total current at zero signal above the safe minimum. Say, for example, you have a 5H choke but at the minimum load the equipment will draw only 40mA. This would lead to a violent rise of voltage. You can add a bleeder that will draw 25–40mA, effectively raising the minimum load to 65 or 80mA. This would get you by the critical knee and would provide good regulation.

TRICKS OF THE TRADE

One advantage of choke input is that the filter capacitors do not handle such high peak voltage or ripple currents. This is important when the supply voltage is close to the maximum rated working voltage of the capacitors. In a 450V supply, 450V or 500V electrolytic capacitors will be much safer with choke than with capacitor input.

There is another trick, too, for improving the filtering of a choke-input filter. It consists of tuning the choke by inserting capacitance in parallel. For a ripple frequency of 120 cps (applicable to full-wave rectifiers) the product of L (in henries) to C (in µF) necessary to achieve resonance is approximately 1.7. To find the approximate tuning capacitance for a given inductance, divide the inductance into 1.7. With a choke of 8H, then, you would need a capacitance of approximately 0.2µF; with 10H you would need about 0.17µF; with 2H you would need a little over 0.8µF, and so on. You will usually have to adjust the capacitance by trial and error.

Take a good-quality paper capacitor (*Fig. 11*), smaller than that calculated, then parallel it with even smaller capacitors until you obtain lowest hum. Again, this measure is effective on the fundamental ripple frequency, but not on the harmonics, though in most cases the harmonic ripple will be better with tuned than with untuned filters. ❖