Realistic Audio Engineering Philosophy

NORMAN H. CROWHURST*

The author presents the why's and wherefore's of the Unity-Coupled circuit which is the basic difference between McIntosh and other amplifiers, and according to the author it exemplifies the progressive approach to amplifier design.

THERE SEEM TO BE two basic approaches to the design of an amplifier. In one a price is decided upon, according to the intended market, and then different circuits are investigated, with careful cost comparisons, to find out how good the amplifier can be made within the price already fixed upon. This approach may lead to extremely competitive pricing of amplifiers but it is not conducive to progressive design. Instead design is tied to old-established readily-obtainable components, and research into new components is to be avoided.

Progressive design cannot be restricted by "what has always been done." The original unity-coupling patent broke away from accepted circuitry, and required one special component to do it—the bifilar-wound output transformer. Pentodes (or tetrodes) had become established as the most efficient way to achieve output power. Operated in Class B, the efficiency is extremely attractive. But certain distortions were previously "inherent" to this kind of circuit. Unity coupling resulted because its inventor did not accept their inherent nature, but found an effective way to eliminate them.

This article does not aim to tell you that the McIntosh line of amplifiers is the best. The often-asked question about which is the "best" amplifier is incapable of an *unqualified* answer. The McIntosh approach is one very good way to make amplifiers whose performance rates high, and it exemplifies the realistic engineering philosophy. But before getting into the real "meat," one minor, but common, source of confusion needs clarifying; the words "unity coupling" are applied to more than one circuit. Beside the circuit discussed here, a variety of single-ended push-pull also has this name.

The so-called single-ended push-pull method of operation uses two tubes in the output, connected in series between B+ and B−. (*Fig.* 1). In the quiescent condition, with no signal passing, half of the total B-supply voltage is across the upper tube and half across the lower tube. Driving the grid of one tube posi-

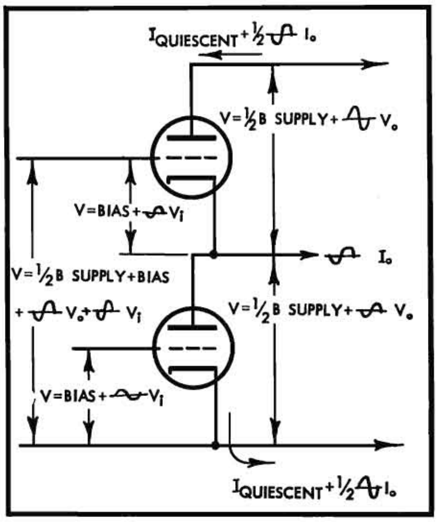

Fig. 1. Signal and supply current relationships in the so-called single-ended push-pull circuit. This also has been called "unity coupled," but is not to be confused with the circuit so named in this article.

tive and the other negative causes the voltage distribution to change. Interposing a load between this center tap point and ground reference, which is at the same a.c. potential as either B+ or B−, causes a variation in current through the two tubes as well as a variation of voltage across them. In this way, by suitable matching, each tube works with a load line very similar to operation in normal push-pull.

One major problem arises with this circuit because the reference point for the upper-tube grid is not ground while that for the lower one is. This means that the drive excursion provided for the lower tube has to be just the necessary grid drive, while that for the upper tube has to be the grid drive in addition to the audio output voltage. Thus an *unbalanced* phase splitter is needed. This produces a circuit much more susceptible to distortion than is the true push-pull arrangement, even when the correct load resistance is applied to the output. Practical operating conditions, of course, never apply the true load resistor for which the amplifier is designed, but a loudspeaker, in which the load impedance deviates with frequency and includes reactive components. With this kind of a load, one tube produces all the output, while the other produces all the distortion.

Some variations of the single-ended push-pull circuit use a feedback compensating arrangement that readjusts the grid drive to the two tubes to balance out for this variation. However, even with such arrangements, the basic circuit introduces more distortion than the conventional push-pull arrangment.

The redeeming feature in the claims made by the designers of the single-ended push-pull circuit is the large amount of feedback that can be applied, due to avoidance of the hitherto necessary output transformer. This design permits as much as 40 db of over-all feedback to be applied. Thus, even with distortion figures in the region of 40 per cent, it is possible to end up with a resultant distortion in the region of 0.4 per cent, which looks quite an acceptable figure. But this figure overlooks two important facts: (1) the nominal figure of 0.4 per cent distortion is only obtainable *working into a resistive load,* such a circuit must inherently produce much more distortion when practical loads are applied; and (2) even the 0.4 per cent is relatively high distortion.

The idea that avoidance of the output transformer has automatically freed us of many of the distortion problems that have come to be regarded as coincident with this component is mere wishful thinking. Unity coupling, however, is built around a rather special kind of output transformer.

Class-B Operation

For some time now it has been realized that the most efficient output tube to use is a pentode or beam tetrode, and further, the most efficient way of using a pair of output tubes is to work them in class B, or as near to this condition as possible, so that the quiescent current is

* *216–18 40th Ave., Bayside 61, N.Y.*

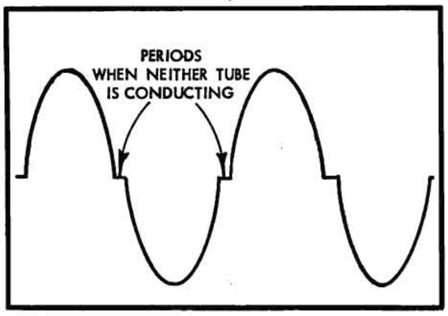

Fig. 2. Effect of overbias of class-B output tubes on waveform, showing crossover distortion.

quite low and large plate current excursions are only drawn when there is a large audio signal.

One of the problems of class-B operation is that incorrect bias can produce a form of distortion known as crossover distortion. This is due to the fact that transition from operation with one tube in one half cycle to the other tube during the other half cycle is not a smooth one. Crossover distortion shows up when the tubes are over-biased so there is a short period during which neither tube conducts current. This produces the waveform shown at *Fig.* 2.

In the early days of class-B operation much was said about this form of distortion, although it proved to be fairly easy to eliminate it by careful attention to bias arrangment. Some of the early class-B amplifiers, using transmitting type triodes with higher-than-normal plate-supply voltage, and extra high grid bias to match, were extremely efficient amplifiers in the higher wattage ratings. However, these amplifiers required extremely carefully designed drive as well as output transformers and a very well regulated plate supply. And the use of at least two transformers in the amplifier rendered them difficult for application of any degree of feedback, although the distortion of well-designed units was not more than that of well-designed class-A amplifiers of the period.

Improved tube techniques led to the use of pentodes and beam tetrodes more extensively as output tubes and circuits employing these could certainly deliver a bigger output more efficiently than their earlier predecessors. The one fly in the ointment about using beam tubes or pentodes in class-B operation proves to be the so-called "notch" distortion. This has been confused with crossover distortion but it is not the same thing. To some extent it is due to *similar* causes. Both distortions occur with tubes biased to operate in class-B.

While notch distortion proves almost impossible to avoid with pentode or beam tetrode output tubes, using normal transformer construction methods, it is not limited to these tube types. The lower plate resistance of the active tube in a push-pull triode circuit can contribute to the damping of the notch oscillation, which will not happen in the pentode circuit. The notch is excited by the sudden transfer of plate current from one half of the primary winding to the other, which triggers the resonance of the inactive winding, between its self-capacitance and the leakage inductance to other circuits, the secondary with its load, and the other half primary with its tube plate resistance.

The leakage inductance resonating with primary capacitance is damped only by the load resistance on the secondary (usually in between the two primaries) and by the plate resistance of the tubes in shunt with the effective resonant circuit. (*Fig.* 3). Plate resistance in a class-B circuit has a widely fluctuating value and in effect becomes almost open circuit at the crossover point, which stimulates the resonant circuit at the point where it is shock excited, especially when the exciting frequency becomes higher so as to approach more closely the resonant frequency.

For this reason, with even a moderately well-designed output transformer an amplifier employing pentodes or beam tetrodes in class-B push-pull would produce notch distortion at frequencies from 3000 cycles and up. It might be thought that over-all negative feedback would successfully eliminate the notch. But this does not occur, because the resonant frequency of the notch itself is also at a point where the feedback stability characteristic approaches its marginal condition. This means that, at best, the feedback will not improve the notch distortion and, at worst, it may considerably exaggerate it.

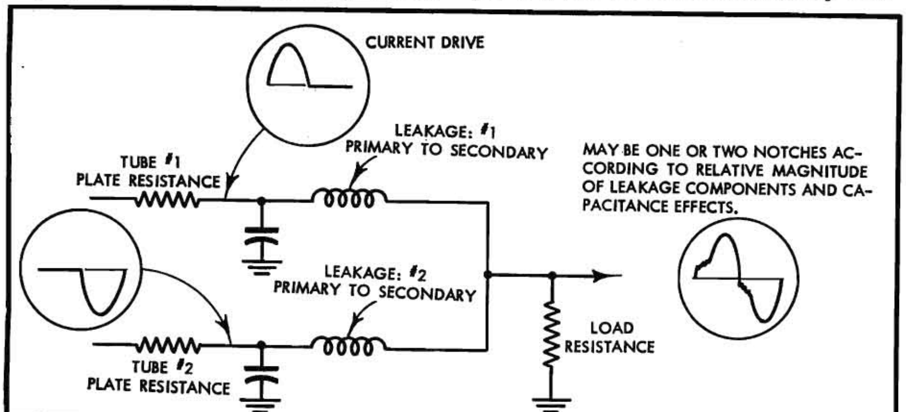

Fig. 3. Equivalent circuit of the quantities that cause "notch" distortion.

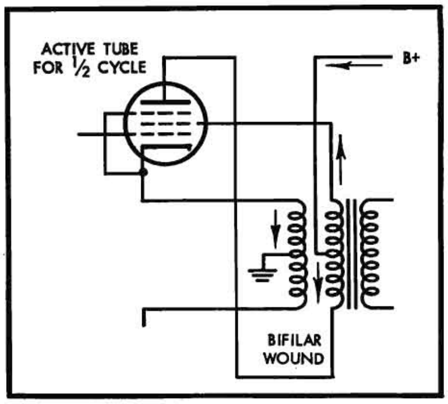

Fig. 4. How the bifilar-wound, unity-coupled circuit avoids the leakage flux transfer impulse that causes notch distortion. As plate current is equal to cathode current minus screen current, the effective current in both half-windings (regarding the bifilar pair as a unit) is always equal.

Eliminating Notch Distortion

How then can notch distortion be eliminated from this kind of output circuit? Two steps can be taken towards this end: (a) to bring the resonant circuit causing notch distortion nearer to critical damping; (b) to eliminate the excitation of the notch, due to the effective transfer of current suddenly from one winding to another.

Using straight pentode class-B operation, it might be possible to reduce primary capacitance by careful winding procedure. But this would merely push the notch frequency (i.e. its sharpness) out further, by raising the resonant frequency and correspondingly raising the point of marginal stability, where feedback ceases to help.

Reducing the leakage inductance, on the other hand, will increase the damping provided by the load. While this might conceivably eliminate notch distortion *into a resistance load,* it might reappear when a reactive speaker load is used.

Excitation of the notch occurs due to leakage inductance *between halves* of the primary, so that transfer of current from one half to the other induces a voltage kick in this inductance. Part of the solution, then, rests in eliminating or minimizing the leakage inductance between halves of the primary winding. Adequate results could probably be obtained by reducing the referred leakage inductance between primary halves to a small fraction—in the region of 1/10—of the leakage inductance between the primary and secondary. This method is necessary for a transformer intended for ultra-linear operation, if the ultra-linear

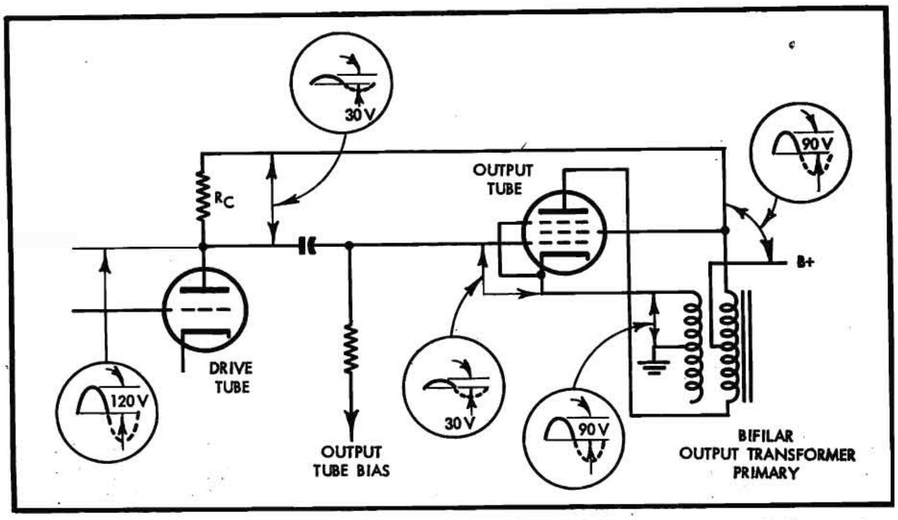

Fig. 5. How the bootstrap circuit works, by making the screen swing help produce the required grid drive. Dashed portions of the small waveforms indicate the part during which the output tube shown is inactive and the other one takes over.

counterpart of notch distortion (an even worse animal) is to be avoided.

However, the approach adopted by McIntosh is more of the "brute force" type, by reducing the leakage inductance between primary halves to vanishing point with the use of bifilar windings. At the same time the use of unity coupling makes a double step to prevent any kind of load from allowing even a suspicion of notch distortion to return. (See *Fig.* 4).

In the first place the significance of the term "primary half" is changed. The primary winding is divided, not in two parts as in the normal push-pull, but into four parts. The whole of the winding connected in the cathode circuit is wound bifilar with the whole of the winding connected in the plate and screen circuits. In this way an equal number of primary turns is interposed between cathode and ground as that between plate or screen and B plus. The cathode and screen of each tube are connected to the same end of the bifilar pair while the plate is connected to the opposite end. As the two windings are wound in such close proximity as to be virtually only one winding, this means that each of the tubes is effectively connected across the whole of the primary winding. When, during one peak of an audio signal, only one of the tubes is conducting, the whole of the primary winding, in effect, is carrying the current of this tube, one half of one of the bifilar windings carrying the plate current, while the other half of the other bifilar windings is carrying the cathode current (see *Fig.* 4).

This means the effective leakage inductance between the circuit that conducts during alternate half cycles, when transition takes place from one tube to the other, is so small as to be negligible. Leakage inductance between primary and secondary, of course, forms one of the parameters for the design of the over-all feedback network, but this does not introduce any form of notch distortion, because it is not interposed between these two output tubes themselves.

50 Per Cent Feedback

The second advantage of the unity coupling arrangment is that it provides what may be called 50 per cent feedback. This means that the β of the plate circuit of the combined tubes is effectively 0.5, and half the output voltage is developed between cathode and ground and half between plate and B+. This reduces effective plate resistance "seen" by the combined primary of the transformer to a point that constitutes more-than-critical damping of the resonance primary capacitance and leakage inductance at all points on the waveform, and into all kinds of output load.

As with other circuits of this type, a very large grid swing is required to provide the necessary grid-to-cathode drive voltage, in addition to the cathode-to-ground half of the output voltage. This cathode degeneration also provides from 12 to 15 db under nominal load, according to tube type and operating conditions chosen, of linearization. This results in a damping factor between 4 and 5 before any over-all feedback is applied (this will be slightly modified as we shall see later, by the drive arrangement).

An interesting point to note here—not exclusive to this circuit—is that the damping factor of a pentode output stage, calculated on the usual basis of on-load gain, is approximately independent of the plate resistance of the tubes. A gain reduction, onload, of 4:1 (12 db) yields a damping factor of 4. The gain reduction of the circuit without the load would be at least 20 db greater than the calculated figure, because the gain of the tubes with open-circuit plate loading rises this much.

There are two advantages to linearizing an output stage in itself rather than by over-all feedback. Use of a tightly coupled arrangement, such as this, makes the degree of linearization practically independent of output loading. With normal pentode operation, changing the output loading can change the feedback from its nominal 20 db or so, up to over 40 db—without taking into account possible phase effects. Utilizing this method gets the damping factor above unity without any risk, and stabilizes the over-all feedback to within a db or so (and phase to a few degrees).

The other advantage is that use of over-all feedback to linearize a distortion basically produced by the output stage *deliberately distorts* the waveform handled by the *relatively* linear part of the amplifier (by as much as 40 per cent in the example quoted earlier). By linearizing the output stage *as an entity*, which is achieved by the use of a circuit such as unity coupling, this problem does not arise. Then the over-all feedback can be used to reduce the residual low-order distortion present in the output circuit to an even lower percentage and to get an even higher damping factor.

Grid-Drive Problems

The next problem with this circuit is the high grid-drive voltage required because of the cathode degeneration. The drive swing required is much more than that normally available at the plate of a preceding push-pull driver stage. The simplest way to overcome this problem (and by far the best) is to use the so-called boot-strap circuit. By coupling the top end of the driver plate resistors to the end of the primary winding of the transformer that swings positive when the grid drive requires to be positive, a form of positive feedback is achieved. (*Fig.* 5).

Assume the grid drive required, from grid to cathode, to be 30 volts and the output voltage per tube 90 volts from cathode to ground and 90 volts from B+ to plate or screen. This means the grid requires a total swing of 30+90 or 120 volts. But by returning the plate-coupling resistor to the 90 volts swing point, there is still only a 30-volt swing developed across it. This means the *effective* value of the resistor, from the viewpoint of the driver plate, is four times its actual value, because the audio current flowing through the actual resistor is accompanied by an audio voltage at the plate four times the audio voltage developed across the resistor itself.

From the d.c. point of view, the drop in the resistor is just that due to its actual value, because the d.c. voltage at each end of the plate and screen winding of the output transformer is sensibly the same as B+. Consequently this positive feedback effect enables a dynamic load line to be employed on the drive tube of

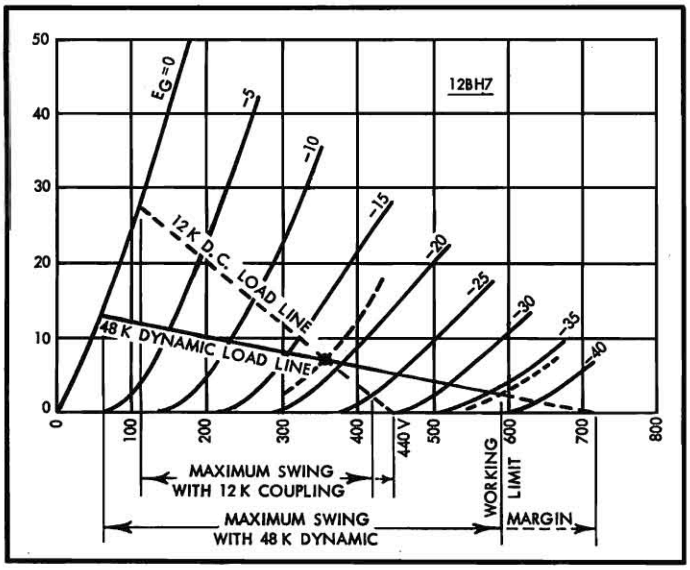

Fig. 6. Operating conditions actually used in the 12BH7 for the MC-30 amplifier, showing how the bootstrap increases the available swing the tube can handle, by a factor much more than it increases its gain.

four times the d.c. value, in this particular example. In other cases it may be more or less according to the degeneration produced in the cathode circuit of the output stage.

This improves the available swing in two steps. First it increases the operating plate voltage and current by allowing a lower actual value of resistor to be used. Then it increases the available audio swing by raising the *effective* value of this coupling resistor. This is illustrated by means of dynamic load lines in *Fig.* 6.

Another way of viewing this is that in a sense now the driver stage only has to provide the grid-to-cathode swing in its plate circuit, instead of the complete grid swing. This being the case one would imagine at first sight that the positive feedback would undo some of the beneficial results of the negative feedback. The reason this does not happen is that the positive feedback is not effectively so great as the negative feedback, although at first sight it might appear this way, because of the change of the effective value of resistance in the plate circuit of the driver tube. Also the positive feedback is not materially dependent on output loading, as is the negative feedback.

In this particular case the plate resistance of the drive tube is in the region of 7500 to 8000 ohms and the plate coupling resistor is 12,000 ohms. This means the realizable *gain* of the tube, without positive feedback, would be approximately 3/5 of its amplification factor. So increasing the *effective* resistance of the plate coupling resistor by positive feedback can only increase the gain of the drive stage by a maximum of 5/3 (assuming the effective value is increased to infinity).

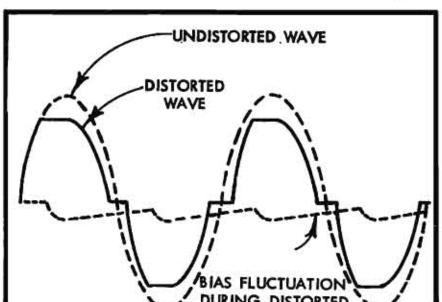

Fig. 7. Kind of distortion often produced in a fixed-bias amplifier, due to grid current biasing back.

Bootstrap Circuit

While this bootstrap circuit only increases the available *gain* of the drive stage by approximately 50 per cent it increases its available *swing* to considerably more than double, because it virtually extends the region of linear operation by allowing a greater grid input swing to be effective. The steeper slope of the 12,000-ohm load line runs into cutoff much sooner than the shallower slope of the 48,000-ohm load line.

The plate resistors for the bootstrap drive circuit need to be of adequate power rating, because the increased efficiency of the circuit raises the available plate-circuit dissipation. They also need to have close tolerance to maintain uniform operating points.

It has often been noted that class-B output circuits often do not *seem* to give so much output as circuits using nearer to class-A operation, using automatic or cathode-bias circuits. The reason for this is traced to what happens when overload begins to occur. The automatic-bias circuit self-compensates for overload by producing cathode degeneration of the overload component of the signal. With fixed-bias circuits, which have to be used for class-B operation, the cathode circuit returns to ground. If the grids make any excursion positive at all, this will produce a negative charge momentarily on the coupling capacitor from the driver plate. This will invariably overbias the tubes for a period of more than the average audio cycle and thus produce quite noticeable distortion very quickly.

Usually the grid resistor has to be of fairly high value to prevent loading down the drive stage. This is still true with unity coupling. Although a 12,000-ohm resistor produces an effective value of 48,000-ohms due to the positive feedback, the grid resistor has to be returned virtually to ground (actually to fixed bias negative) and consequently its effective value is the same as its actual value. If a large value resistor, in the region of 330k, which is usually recommended for this position, is used, the biasing-back effect will last for at least a cycle of the audio waveform, consequently the next excursion through crossover will show crossover distortion, as illustrated at *Fig.* 7.

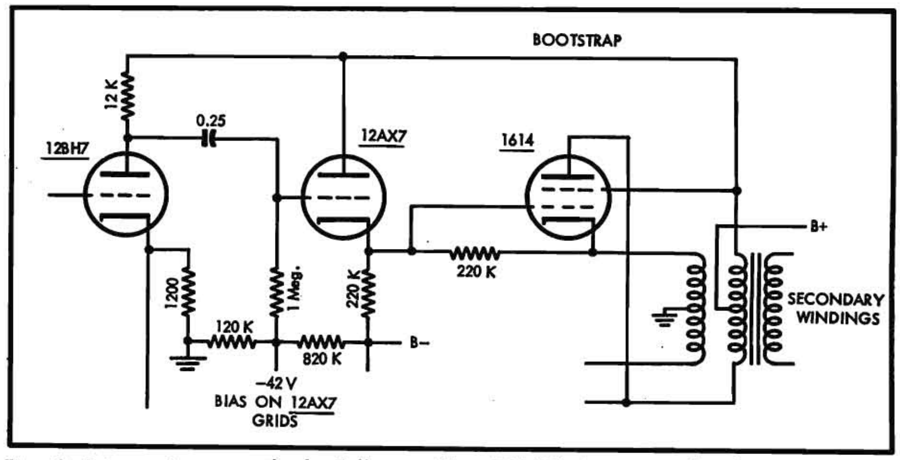

Fig. 8. Interposing a cathode follower (the 12AX7) between the bootstrap drive (12BH7) and the output tube (1614) grids completely prevents the kind of distortion shown in Fig. 7.

This can be avoided by using a capacitor value such that the discharge time is shorter than one period of the audio waveform but this would mean an excessive low-frequency loss due to the combination of coupling-capacitor and grid-resistor values. This may be offset to some extent by the over-all negative feedback, but it increases the demand on

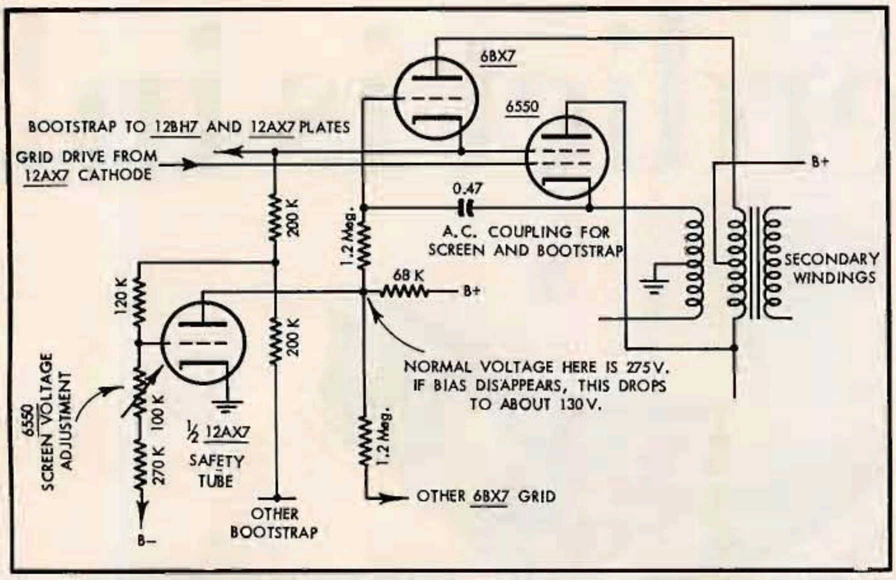

Fig. 9. Addition of another cathode follower (6BX7) to feed the screen of the output tube (as well as the bootstrap) enables unity coupling to be applied to tubes using pentode operation with different quiescent plate and screen voltages.

the driver stage at the low-frequency end to an impossible degree.

The only positive way to eliminate this effect is to have the output tube direct coupled to the tube that immediately drives it. This is possible by using a cathode-follower stage interposed between the bootstrap drive stage and the output tube grid. The driver stage can then be resistance/capacitance coupled to the grid of the cathode follower stage and everything works quite happily.

The cathode-follower stage is bootstrapped as well, which enables a low-current high-mu tube, such as a 12AX7, to be used to good advantage (*Fig.* 8). Although the actual resistance, from cathode to the negative return point necessary to provide the correct operating condition for the tube, is of value 220k, the effective a.c. resistance at this point is in the region of 600 to 1000 ohms—the effective cathode resistance of this tube operating as a cathode follower.

Direct bias for the output tube is controlled by the grid bias of the cathode-follower stage. To achieve this the negative voltage provided for the cathode return of the cathode follower is potted down by two resistors so that the negative point for the grid circuit is just right for the output tubes.

Just one more refinement to be necessary. Before the tube starts to conduct, during warm-up, the cathode of the 12AX7 and the grids of the output tubes are at the maximum negative potential of this return point, because there is no current flowing through the cathode resistor of the 12AX7. This means the cathode/heater potential of the 12AX7 can be excessive. To avoid this possibility a further resistor of 220 ohm is connected between cathode of the cathode follower and cathode of the output tube, thus forming a voltage divider to limit voltage during warm-up. In operation this will only have small audio voltage across it, and consequently represents negligible audio loading.

One more circuit has been developed for use with the unity-coupled output stage to enable it to be applied to tubes that can give considerably more output by operating the plates at much higher potential than the screens. To achieve this, a further cathode follower tube is inserted in the screen feed to the output tubes. The grid for this cathode follower derives its audio voltage from the cathode of the tube it feeds, while the d.c. potential is supplied through a separate control tube, half of a 12AX7, which combines a safety function, making the screen voltage drop almost to zero in the event the grid-bias voltage should disappear for any reason. This action is illustrated in the partial schematic of *Fig.* 9.

The feedback arrangement of the unity-coupled amplifiers is pretty much in conformity with general feedback practice, utilizing a resistor with phase-correcting capacitor from the secondary of the output transformer back to the pre-phase-splitter cathode.

The Output Transformer

In some of the more modern unity-coupled amplifiers, the output transformer has been elaborated somewhat from the simple bifilar arrangment originally used for providing just loudspeaker impedance tappings. For some applications a 70-volt or 600-ohm tapping is required. One method of achieving this was take tappings from the primary side, utilizing the section connected to ground in the cathode circuit. A 70-volt output could be achieved by using the ground point and a suitable tapping, while the 600-ohm output requires two tappings, or in some instances a connection to the tube cathodes. (*Fig.* 10).

A disadvantage of this method for some systems is that the 600-ohm or the 70.7-volt circuit, as the case may be, is permanently attached to the amplifier ground, because it uses the actual cathode winding. To overcome this disadvantage, so that ground isolation can be achieved when necessary, either for hum reduction in the system or to conform with system regulations, the output transformer is stepped up from *bi*filar windings to "*tri*filar" windings. In this way a section of the transformer, wound at the same time as the primary, is used for the high-voltage outputs, 70 volts and 600 ohms, while a separate winding, wound bifilar with the secondary, is used for the feedback. This enables the secondary also to be isolated. In some instances parts of the secondary are also wound trifilar to enable other combinations of impedance to be achieved, not so readily possible with just a single winding.

There is one more important feature improvement in the unity-coupled circuit from the original arrangment. This is a device to improve the transient-handling capacity of the amplifier. Because the amplifier uses resistance smoothing, the impact of a transient alters the supply voltages. These voltage changes can put an asymmetrical transient through the system, because they get referred to the single-ended part of the amplifier.

To overcome this effect, a "long-tailed" splitter is used in which the grid return for the second half of the inverter is not coupled directly to ground, but through a time-constant circuit that produces an

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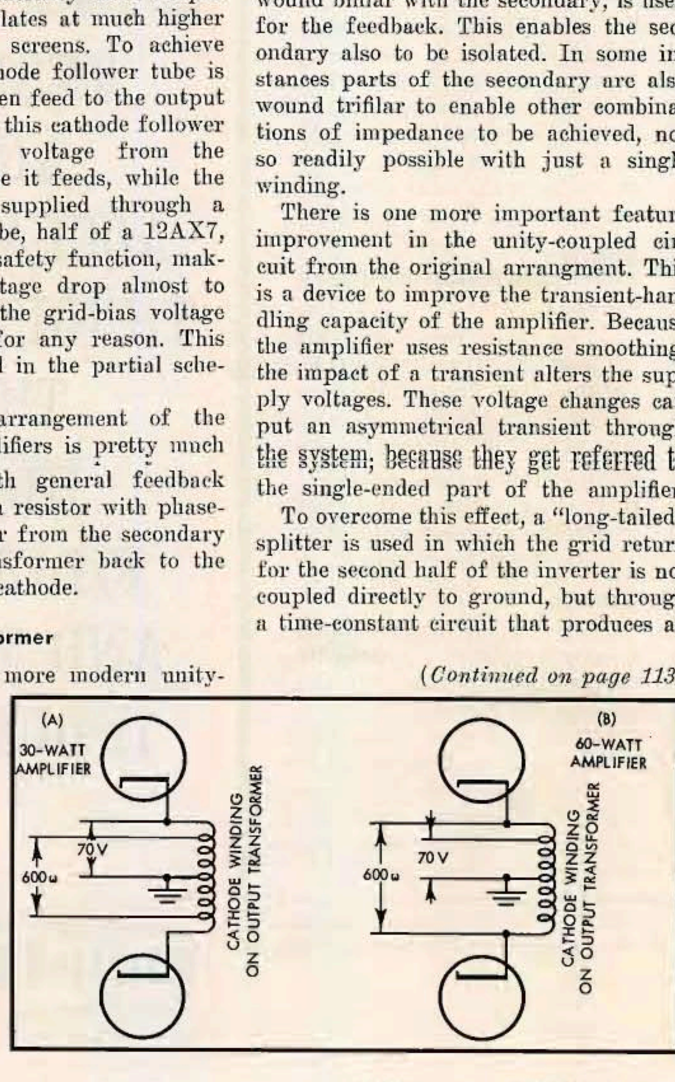

Fig. 10. Different ways of picking off 600-ohm or 70-volt outputs, according to power and impedance of the output circuit. In some professional types, these tappings are separated by trifilar winding.

to a point of satisfying high-fidelity standards. If that could be done, then very interesting possibilities exist.

A seven-inch reel of long-play tape runs for a full hour at 3¾ ips. With ten recordings on the tape, it would play for a full ten hours! This is not only competitive with LP records—it is superior on a straight dollar-and-cents basis. The cost of reproduction should not increase, since multiple heads could be placed "in-line" and all recordings made in a single pass of the tape.

Intriguing? Æ

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identical effect with that present in the first half. (*Fig.* 11). In this way the asymmetrical effect of the long-term time-constant changes in the supply circuit are neutralized out so that no component of this appears beyond the phase inverter. This results in an amplifier that does not get shock excited into bounce effect when sudden transients hit it.

There is one more variation of the unity-coupled circuit that this company has produced, using triodes in class-B instead of pentodes. In this case two transmitting type triodes, 8005's, are utilized for the output. The boot-strap method is used for the drive stage in just the same way as for the pentode circuit. But in this case tetrodes are used for the drive function. (*Fig.* 12). This is because the whole proportions of the output circuit are changed.

With pentode operation the cathode degeneration is responsible for reducing the effective plate-circuit resistance or source resistance for the output stage from its original very high value to a fraction of the load resistance. Hence a relatively low-resistance triode is necessary for the drive stage, in conjunction with the regeneration of the boot-strap circuit, to prevent complete loss of this improved output impedance and linearization. Using triode output tubes, the picture is practically reversed.

The plate resistance of the tubes is not larger than the load resistance to begin with. In a class-B circuit it is approximately of the same order. The cathode degeneration due to unity coupling reduces this to a lower figure and the regeneration of the boot-strap circuit can be permitted to bring it back approximately to its original region. What is more necessary with a triode output circuit is a bigger swing for the output-tube grids, because of the longer grid base of these tubes as compared with corresponding pentodes. For this reason a pentode, operated with a low-value plate resistor and using regeneration to multiply the effective value of the re-

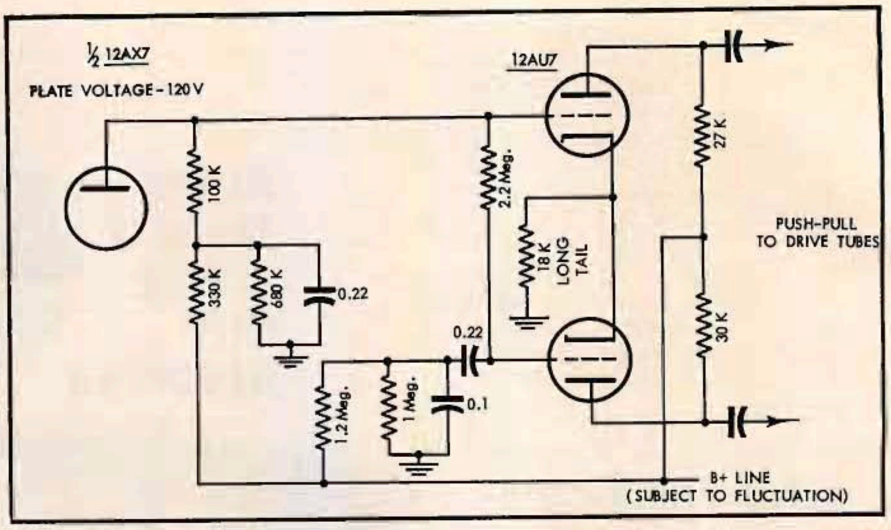

Fig. 11. The modified "long-tailed pair" phase-split inverter, designed to compensate for B+ line fluctuations (due to transient changes in signal level) that otherwise can cause erratic amplifier behavior.

sistor, enables the much bigger needed swing to be obtained.

Again, cathode followers are used to drive the triode grid directly and avoid the effects previously mentioned and also to enable the tubes to be driven into the positive grid region to get power drive.

Apart from these slight differences, the circuitry of the 200-watt unity coupled amplifier, using two 8005 triodes for the output, is very similar to the other circuits we have already discussed.

It will be noticed that the circuitry we have discussed in this article is different from that employed by many amplifiers in that it has been engineered to serve the purpose intended, not just taken from current practice and reduced to a minimum for economic purposes. Having engineered a working circuit the McIntosh people have then worked on their production technique to obtain a satisfactory price. Æ

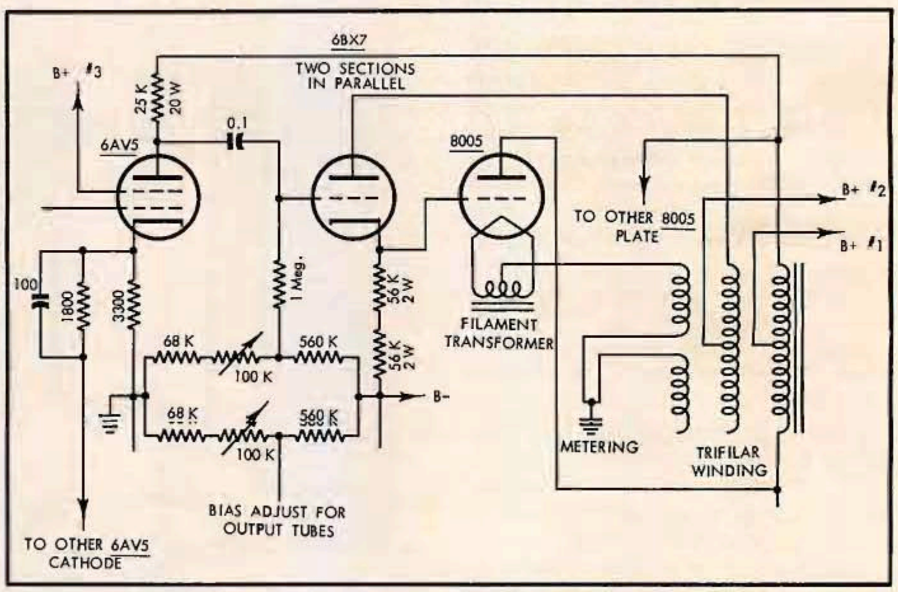

Fig. 12. An "inversion" of the unity-coupled circuit uses a transmitting triode in the output, with a pentode bootstrap drive. With power drive of the 8005's, this circuit delivers 200 watts.

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channel as shown in *Fig.* 4. Such a transformer must be able to handle the full power output of one channel, and must be of high efficiency to conserve valuable audio power. The transformer should also be bifilar wound to introduce the least possible degradation of the high-frequency power response. Since commercially available units meeting these requirements could not be located, special transformers were constructed. The size and cost of each proved to be substantially equal to the output transformers used in the amplifier.

Another satisfactory method, but requiring a special amplifier or modifica-