The first major change in years in amplifier coupling circuit principles is discussed, together with details of the components employed.

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and

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Description and Analysis of a

New 50-Watt Amplifier Circuit

AUDIO AMPLIFIERS—being one of the oldest forms of equipment built using the three or more element tube—are now one of the most difficult devices to improve, and perhaps no other field of electronic endeavor has been given more time or has been studied by more people. One of the major reasons sound amplifiers are difficult to design is the requirement for very wide frequency range, highest to lowest running up to 20,000 to 1 in order to meet the ever-increasing demand for more faithful reproduction of the audio range of from 18 to 20,000 cps. This wide range is probably the most rigid requirement for any electronic device regardless of its use. To satisfy the design requirements for an audio amplifier, several problems must be overcome. At the low end of the audio band the requirement for sufficient core material of proper magnetic properties must be weighed against core loss, weight, size, and expense. These quantities bear an inverse relationship to the total number of turns, but the total turns bear an inverse relationship to the leakage inductance and the effective shunt capacitance. At frequencies of 3,000 cps and higher the shunt capacitance across the primary circuit of output transformers becomes one of the major limiting factors, regardless of the mode of operation of the output stage. When the output stage is operated Class AB or Class B to improve the efficiency, then an additional problem growing out of the switching from one side of the circuit to the other in the output stage and thus producing a transient has been a barrier for over 20 years and has made practically useless such circuits except in applications where the harmonic content was not of great importance or where the range was limited over which such circuits are operated. This transient appears as a notch in the signal wave form and was first described in 1936[1] but for which no solution was suggested beyond that of reducing the leakage inductance of the output transformer or of biasing the amplifier stage back to Class A operation.

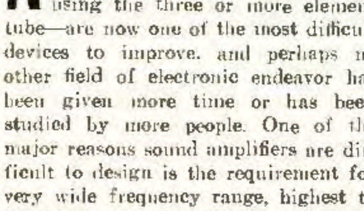

Fig. 1. Simplified output circuit of conventional push-pull amplifier.

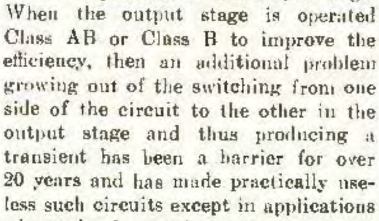

Fig. 2. Oscilloscope trace showing notches in output wave when operating between Class A and Class B.

The basic circuit which we are about to describe grew out of an attempt to meet many considerations and requirements based upon tests and measurements made concerning the ability of the ear to detect distortion, the range and power of speech and musical instruments, the impulse characteristics of sound, the load impedance variations and effects of loudspeakers and other devices. A treatment of these basic requirements must be reserved for a later discussion.

Output Circuit

Figure 1 illustrates the output circuit of the conventional pushpull amplifier in simplified form. It will be seen that the plates are connected in the conventional way to the primaries of the output transformer and the resistor forming the load is shown connected to the secondary. The plate-to-plate impedance in this circuit is 4000 ohms. This is about right for a pair of 6L6's as used in the McIntosh 50W-1 amplifier. Attention is called to the 1000-ohm impedance which corresponds to the circuit from the plate to the center tap of the primary of this output transformer. These impedances should be born in mind as later reference will be made to them as part of the description of the new circuit. In the discussion to follow it is assumed that each of the tubes in the output circuit alternately cease to draw current during a portion of the audio

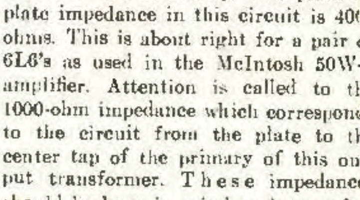

Fig. 3. Trace showing transfer characteristic of output tubes with discontinuity due to notch of Fig. 2.

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[1] A. P. Sah, Quasi-Transients in Class B Audio Frequency Push-Pull Amplifiers, *Proc. IRE*, Nov. 1936.

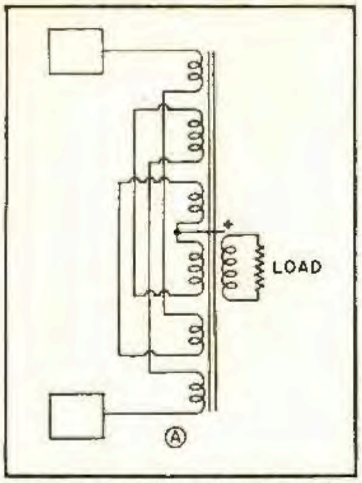

Fig 4. One method of minimizing leakage reactance by use of sectionalized primary winding.

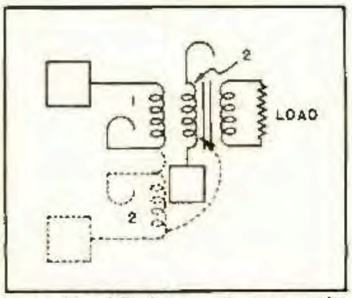

Fig. 5. Simplified form of new coupling arrangement for amplifier output stage.

cycle and, therefore, are operated somewhere between Class A and Class B.

Experience has shown that using the circuit of *Fig.* 1 and operating between Class A and Class B will result in a deformity, appearing as a "notch" as shown in *Fig.* 2 for all frequencies above approximately 2,000 to 3,000 cps. This waveform distortion measures 2 to 10 per cent or more depending upon the frequency and the leakage reactance existing between the two primary windings. This "notch" occurs because there is a residual leakage inductance in the plate circuit of each of the output tubes which becomes a source of voltage independent of that voltage driving the stage at the instance when one tube ceases to draw current and the other tube draws more current. This residual inductance or leakage reactance acts like an inductance through which the current has suddenly been cut off, and it generates a back e.m.f. which distorts the output wave. The value of this leakage reactance must be minutely small so that the distortion of the wave form at the highest frequency will not exceed 1 per cent. This effect has no panacea, so far as we know.

Negative feedback, the usual panacea, does not improve the situation, as might be expected, but rather tends to make it worse. To cancel the notch in the waveform a current flow would be required through the tube in the reverse direction to that which the electron flow permits, at the time the tube ceases to draw current during the normal cycle of operation. Another way to describe what happens in the circuit is to consider *Fig.* 3. Here is shown an oscillographic trace of the transfer characteristic of the output tubes. The presence of leakage reactance between the two primary windings causes a discontinuity to exist in this characteristic. This is the barrier which has been the source of frustration of many engineers for years past and is perhaps the major reason that high efficiency and low distortion could not be made compatible.

Reducing Leakage Reactance

There are a number of approaches aimed at reducing the leakage reactance but the penalty has been so great that the value of the increased coupling between primary windings has been offset sufficiently to make these approaches no solution at all, or of little value. *Figure 4* shows symbolically the sectionalizing of the two primary windings shown in *Fig.* 1. Here the primary is made up of many coils which are connected in such a fashion as to tend to make all the windings occupy the same space. This is an effective means of increasing the coupling between two coils and does increase the frequency at which the "notch" first appears. However, this approach has the disadvantage of increasing the shunting capacitance effects between the two plates of the circuit to such an extent that the high frequencies are by-passed. There doesn't seem to be any practical way to sectionalize and interleave these windings to eliminate the leakage reactance effect

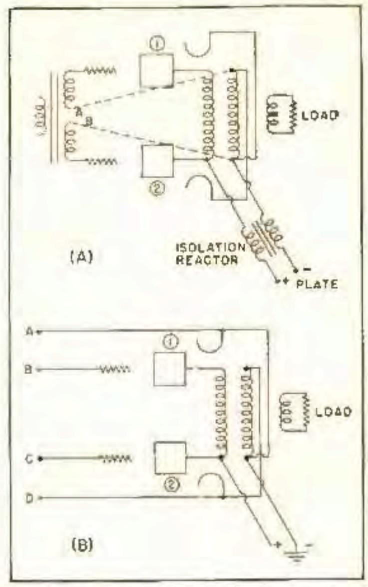

Fig. 6. Steps in development of coupling circuit.

and at the same time avoid the shunt capacitance effects. Another method which suggests itself as a result of the experience just described is to use a much larger core, permitting a reduction in the number of turns required in the windings of the primary circuit. This approach requires a very large core in the order of 125 pounds to effect a sufficient reduction in leakage reactance. This compares very unfavorably with the 11-pound core required in this new unity coupled output circuit for the same performance. It may be well to mention here also that the use of a large core has several other disadvantages among which is higher distortion, particularly at low output levels. This is due to the non-linear characteristics of the magnetic material and the relative-

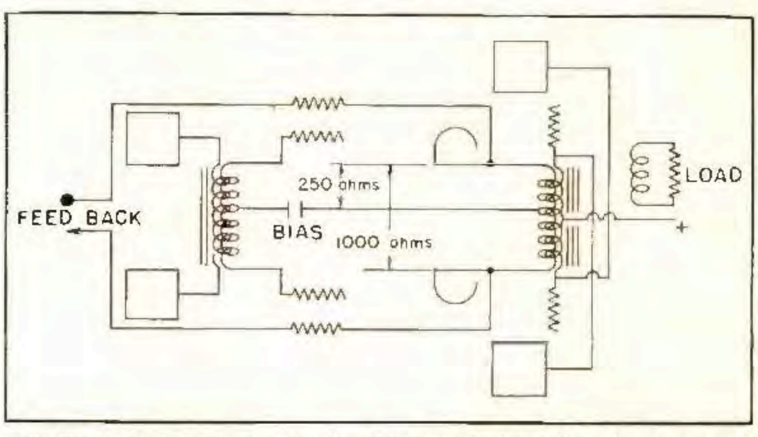

Fig. 7. Final basic arrangement employed to provide d.c. voltage for screen grid, but at the same a.c. potential as the corresponding cathode.

ly larger total loss in the larger core. It would be well to point out at this time that for 6L6 tubes operated in Class AB or Class B, the ratio of inductive reactance of the primary of the output transformer to the leakage reactance between the primaries must be 80,000 to one or greater to permit 1 per cent distortion at 20 kcs and full output to as low as 20 cps.

From the above discussion it seems impractical to reduce the leakage reactance sufficiently to permit high-efficiency operation and the only hope, therefore, is to go back to a conventional Class A arrangement where a discontinuity in the current drawn by each of the tubes does not occur over the operating cycle. The solution for high efficiency operation requires an unconventional circuit which will effectively eliminate the leakage reactance between the primary windings.

Figure 5 illustrates the approach made to circumvent the problems described above. The conventional output primary circuit is again shown with the primary marked *2* in dotted form. For simplicity the power supplies are eliminated and the midpoint of this primary is shown connected to the associated cathodes. The solid position of primary *2* is shown adjacent to primary *1* and this illustrates the first step in the development of the unity coupled amplifier. These two primaries are wound

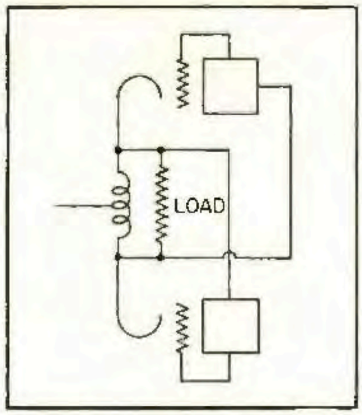

Fig. 8. Equivalent circuit simplified from Fig. 7.

together in a bifilar manner as if they were one winding and, therefore, there is between them both a capacitance coupling turn by turn, and a magnetic coupling due to the presence of the common core. Since the wires occupy practically the same space, the coupling is exceedingly high and measurements show that it is practicable to wind coils with a ratio of primary inductance to leakage reactance much better than 200,000 to 1. This, therefore, provides a way to eliminate the leakage reactance which in conventional transformers far exceeds the minimum ratio requirement of 80,000 to 1. We now, therefore, have a system which appears to have promise by reason of finding a way to eliminate the leakage reactance between the primary windings which in turn removes the barrier which has blocked for so many years the use of high-efficiency circuits in high quality audio amplifiers.

It is obvious that other variations of approach have been considered which accomplish the desired purpose to some extent at least, such as winding the two primaries on a common core not bifilarly and utilizing a suitable capacitance for couping the ends of these windings so as to maintain the two windings at proper and identical a.c. potentials. One advantage of the bifilar winding is, of course, a reduction of the number of components required, and it sidesteps some of the difficulties which grow out of the use of alternate approaches. It may also be obvious here that since the two primary windings are unity coupled there is no longer any need for sectionalizing the primary as is common in high quality transformers today. This results in an economy in manufacture.

Circuit Arrangement

To make *Fig.* 5 a practical circuit, the cathodes are connected to one coil and the plates to the other coil without changing their position in the circuit from an a.c. standpoint but permitting

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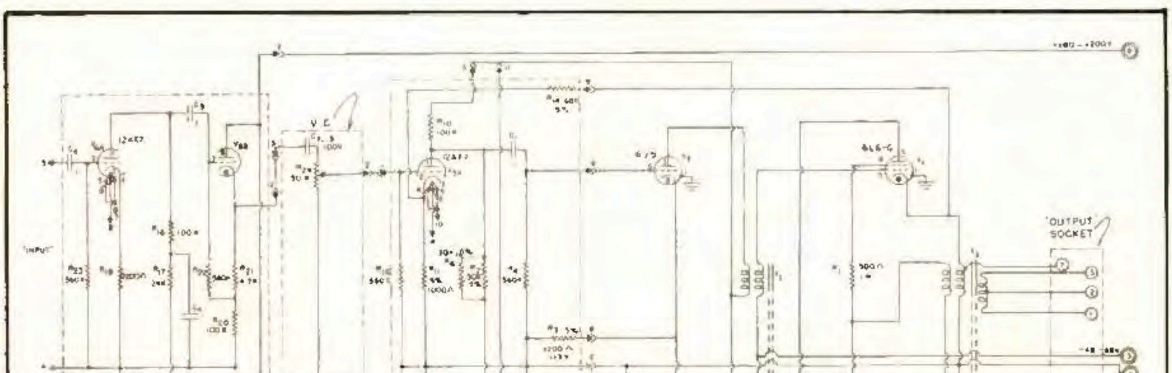

Fig. 9. Schematic of McIntosh 50W-1 amplifier.

50-WATT AMPLIFIER

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the application of the d.c. plate supply between these coils.

Figure 6 (A) illustrates a further step in the development of the final circuit and shows a cathode-loaded arrangement with a required plate supply isolation reactance. Here it will be seen that the cathode loading results from the method of drive. For instance, tube *1* is driven from the control grid to the far side of its load which is, from an a.c. standpoint, at the same potential as its plate, and similarly tube *2* is driven in a like symmetrical manner. In order to drive the stage, it is necessary to do two things: to provide an input transformer or similar device and to provide an isolation reactor which has sufficient impedance to keep the plate supply and the amplifier stage isolated from an a.c. standpoint. It will be seen here that the entire stage is floating with respect to ground. At points *A* and *B* in *Fig.* 6(A) it will be noted that the full voltage developed across the output stage appears to add to the difficult problem of designing a driver transformer able to handle the large voltages needed to drive the output stage. These difficulties—as well as the requirement for wide frequency range, balanced couping, and high impedance primary—make this transformer somewhat impractical if not impossible.

Deleting the isolation reactors from the circuit of *Fig.* 6(A) gives the circuit of 6(B) in which the two cathodes remain at the signal potential difference of the output transformer primary, but one cathode has been returned to ground while the other is left floating. Again the design of an input transformer is highly impractical.

An attempt, therefore, was made to get away from the four-terminal input circuit required by *Fig.* 6(B) and go back to the conventional three-terminal input if at all possible. This was accomplished by the circuit as illustrated in *Fig.* 7, which is similar to those of *Fig.* 6 except that instead of driving the stage fully cathode loaded, the point *A* of *Fig.* 6(A) was connected to the mid-point of the cathode winding which, of course, suggested that point *B* be connected to that same cathode mid-point. We now, therefore, have our three-terminal conventional drive circuit, and furthermore we find that this mid-point can be grounded, which immediately suggests that the plate supply can be similarly attached to the mid-point on the plate winding of the output transformer, and finally this elimi-