

Cathode-Follower

Excellent square-wave response from 10 to 40,000 cycles is obtained from eight double triodes directly driving loudspeaker voice coils. Direct-coupled stage has power gain of 37 db. Up to 20 tubes can be used for auditoriums

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MANY AUDIO EXPERIMENTERS, including the authors, have felt that the power cathode follower was the ideal audio amplifier output coupling stage into a speaker system. Heretofore, either preliminary investigation or practical circuit design has led previous attempts to utilize the cathode-follower power stage into the compromise of coupling the speaker or speaker system with an output transformer.

Such an arrangement has gained some advantages, notably, good frequency response, excellent damping qualities and low distortion. The transformer has, with all its design problems, still been the limiting component of such an audio amplifier. Disadvantages, such as low efficiency and low power sensitivity inherent with this device might be ignored by those seeking true and distortionless reproduction. On the other hand, the lack of voltage amplification of the cathode follower imposes such severe requirements upon the preceding driver stage that the avoidance of distortion is very difficult, if not quite impossible.

The authors have felt strongly that if an arrangement could be developed to couple the cathode-follower stage directly to the voice coil of the speaker, or dividing network of a speaker system, many real advantages would accrue. Initial investigation of such a power cathode follower using the 2A3 class of triodes was not too encouraging; the ideal remained without practical implementation.

In 1946, the introduction of the

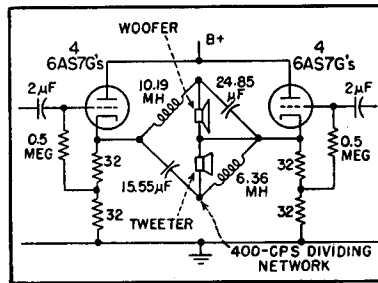


FIG. 1—Basic cathode-follower stage for direct coupling to low-impedance voice coils

twin-power triode type 6AS7G revived interest. Single-ended and balanced arrangements were tried using inductive and capacitive coupling, but finally a direct-coupled, push-pull balanced stage evolved. Figure 1 shows a schematic of a cathode-follower stage utilizing a total of eight twin-triodes of the 6AS7G type. Such a balanced stage retains all the inherent advantages of a push-pull amplifier and permits direct coupling to the low-impedance voice coils with no direct-current flow through these coils.

Balanced Stage

An equivalent circuit of this balanced stage containing eight tubes is shown in Fig. 2. The cathode-follower stage is loaded by the 16-ohm audio load shunted by the cathode resistors, making an effective load of 14.22 ohms driven by a generator having an internal impedance of 23.67 ohms.

For a given number of twin triodes, increasing the cathode-resistor value will make the useful audio power into the speaker ap-

proach a limiting value of $PR_{vc}/2$, where I is the peak current and R_{vc} is the speaker resistance. Decreasing its value will lower the plate-supply voltage and increase the electrical damping on the speaker. Such a design eliminates the output transformer from the audio amplifier, enabling one to build a completely direct-coupled amplifier or an all-stage capacitance-resistance coupled audio amplifier.

The input impedance of a cathode follower is high; this is an obvious advantage. Manufacturers of the 6AS7G recommend that for cathode biasing a grid resistor of not greater than 1 megohm be used to limit ion collection on the grid, thus avoiding erratic operation. For eight paralleled triode sections, a 125,000-ohm grid resistor would be required.

The gas current in these tubes has been low enough to justify a 0.5-megohm resistor, which has proved satisfactory for this cathode-follower service. The high-impedance input into the follower stage allows the use of a simple voltage amplifier as a driver, while a 2- μ f coupling capacitor gives adequately low frequency response.

In addition, the drive voltage is relatively small at each of the output cathodes. With five volts rms phased 180 degrees apart across a 16-ohm load the dissipation is 6.32 watts. Since eight triodes in parallel as a composite cathode follower have a voltage gain of 0.254, the necessary voltage at the grids is less than 20 volts rms. This is a moderate and easily fulfilled condition for a resistance-coupled am-

Loudspeaker Coupling

plifier. The power sensitivity is even greater than the power tubes and transformer combination when replaced by the power cathode follower. An input of 1.32 milliwatts at the cathode-follower grids corresponds to 6.32 watts in a 16-ohm load across the cathodes, a power gain of 37 db!

A square-wave test of the power cathode-follower output stage loaded with a 16-ohm noninductive resistor was so good that the problem of building an amplifier and preamplifier to match its performance became nonconventional audio practice. To avoid angular phasing within the audio range of 20 to 20,000 cps, one might make the empirical stipulation that the amplifier be capable of linear amplitude response from 2 to 200,000 cps.

Square Wave Test

If the amplitude drops 0.1 db at either end of the audio spectrum, a corresponding 10-degree phase shift is suffered while a 3-db drop corresponds to 45 degrees. A balance should be maintained in extending frequency response at both ends of the audio spectrum. That is, if an extension of upper response is made to 200,000 cps, then an extension of the lower response frequencies should be made to 2 cps. One rule of thumb has been to make the

product of the upper and lower half-power frequencies equal to 400,000. Figure 3 shows a schematic of an amplifier that fulfills these conditions. It passes a square wave over the frequency range of 20 to 20,000 cps, which compares favorably with the response of the cathode-follower stage.

Power Supply

Perhaps the most difficult problem to be solved in the design of an amplifier incorporating this power cathode-follower stage is an adequate power supply whose cost, size

and weight remain small. A supply voltage of 200 volts and 2,000 ma will supply sixteen triodes of an eight-tube cathode-follower stage at the manufacturer's recommended operating conditions. This requirement was easily accomplished by using 4 rectifiers, type 872/872A, in the bridge circuit shown in Fig. 4.

The output had a capacity of 2,500 ma, which allowed a 300-ma additional drain for the amplifier heaters. They are in series with a 300-ma field in the tweeter. The woofer field absorbed another 100

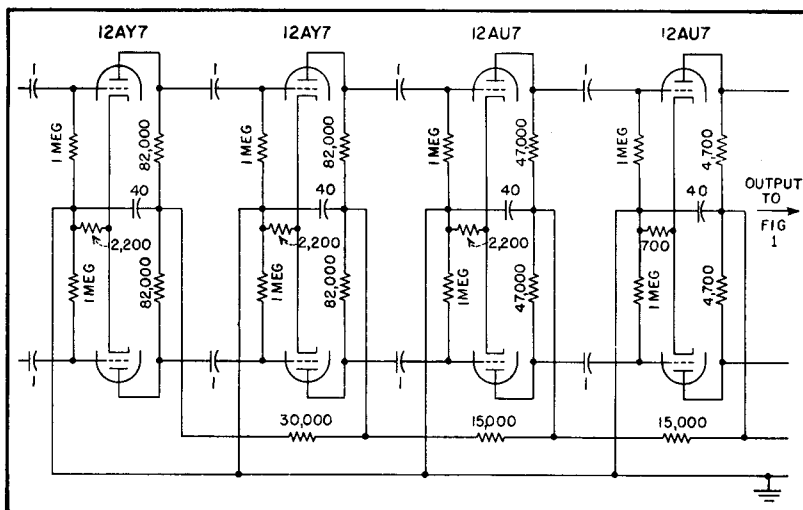


FIG. 3—Suggested resistance-coupled preamplifier with good square-wave response from 20 to 20,000 cps

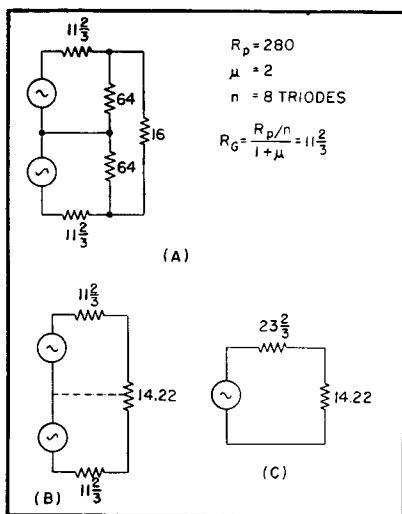


FIG. 2—Equivalent circuit for the eight-tube stage shown in Fig. 1

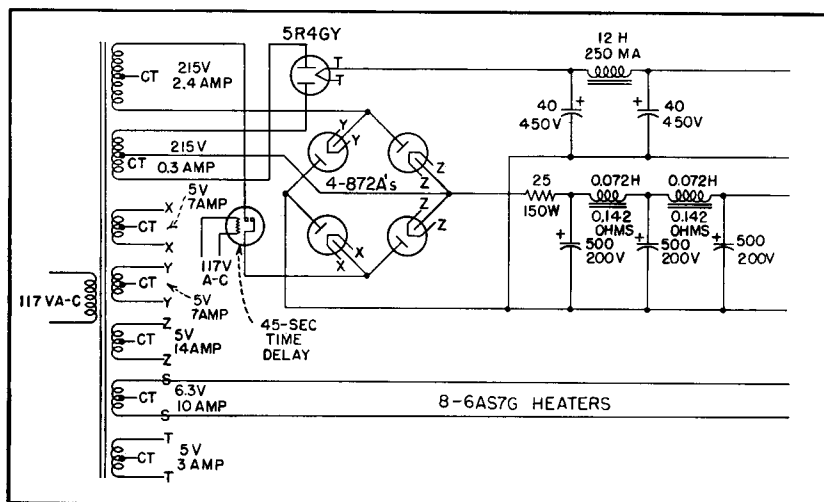


FIG. 4—Unique power supply used to operate the cathode-follower multitube output stage

ma while 50 ma supplied the voltage amplifier. This drain brought the total load on the supply to 2,450 ma.

Pi-section filters, consisting of 500- μ f capacitors and 0.072 henry inductors, adequately reduced power hum in the speakers to an inaudible level, -10 mv of 120-cps ripple. The cost of this supply was held to a ridiculously small figure by utilizing parts available on the surplus market. The extraordinarily low frequency response of the follower makes the hum problem all the more difficult, but the hum level in the balanced output stage itself is down more than 90 db below the maximum output of 6.32 watts for eight tubes. Shot noise, although not objectionable, is more serious than hum. Careful attention to grounding techniques, and the use of an all d-c heater supply in the amplifier kept its hum level below that of the output stage. It might be pointed out that there is no hum pickup problem here such as that encountered with output transformers owing to winding linkage or magnetic coupling.

The maximum audio power output for the cathode-follower stage consisting of eight twin-triode 6AS7G tubes coupled to a speaker system of 16-ohm nominal impedance, where the limiting condition is class A operation, is $I^2R_c/2 = 16/2 = 8$ watts, if the cathode resistor were infinite in value. For the 64-ohm cathode resistors actually used, the total power into these resistors and the 16-ohm speaker system is $I^2R_c/2 = (16 \times 128)/2 (16 + 128) = 7.11$ watts of which only 6.32 watts divides to the audio load while the remaining 0.79 watt is dissipated in the 64-ohm cathode resistors.

In view of the fact that most good audio-amplifier designs claim output powers of 10 to 20 watts, and more recently values even as high as 30 to 50 watts, this value of 6.32 watts seems small. However, with this output cathode follower, the best speakers available are hard pressed even to approach the follower performance. This precludes the use of the output follower with any but the best types of speakers available. Relatively, such speakers are highly efficient.

Table I—Comparison of Multitube Cathode-Follower Stages

Number of 6AS7G Tubes in Stage	4	8	12	16	20
Plate Supply Current (ma)	1,000	2,000	3,000	4,000	4,600
Plate Supply Voltage (volts)	167	199	231	263	282
Push or Pull Composite Tube Characteristics					
Plate Current (amp)	0.50	1.00	1.50	2.00	2.30
Ions Conductance (μ mhos)	28,000	56,000	84,000	112,000	140,000
Plate Resistance (ohms)	70	35	23.33	17.5	14
Cathode Resistance (ohms)	64	64	64	64	64
Bias Voltage (volts)	32	32	33	37	41
Follower Resistance (ohms)	23.67	11.67	7.78	5.83	4.67
Generator Resistance (ohms)	46	23.33	15.56	11.67	9.33
Load Resistance (ohms)	14.22	14.22	14.22	14.22	14.22
Damping Resistance (ohms)	34.33	19.72	13.87	10.69	8.69
Audio Power to Speaker (watts)	1.58	6.32	14.22	22.78	33.38
Audio Power to Cathode Resistors (watts)	0.20	0.79	1.78	2.85	4.17
Voltage across Load (volts)	5.0	10.0	15.0	19.0	23.0
Amplification	0.156	0.253	0.319	0.369	0.402
Power Gain (db)	36.5	37.0	37.2	37.5	37.5
Drive Voltage (Push or Pull) (volts rms)	16.0	19.7	23.5	25.7	28.7
Total Power Input (watts)	320	640	960	1,280	1,600
Overall Efficiency (percent)	0.5	1	1.5	1.78	2.09

A speaker system and dividing network of good efficiency in a room of 2,300 cubic feet volume, with sound intensity distinctly uncomfortable, had a measured average power into the dividing network of only 100 milliwatts. At a comfortable, more desirable level, the measured average power was less than 20 milliwatts!

Average power of 6.32 watts or 12.64 peak watts leaves a considerable factor of safety for the dynamic range required to reproduce a symphonic orchestra over this average power of 0.02 watt. In Symphony Hall, Boston, this may be greater than 90 db above background noise, but a-m and f-m broadcasting as well as record restrictions hold the range below 60 db above noise.

Simplified Amplifier

In the form presented, the cathode-follower power amplifier has low power efficiency as well as poor weight and space efficiency. There is reason to believe that a follower stage, utilizing only four twin triodes of the 6AS7G type, will do as well except for a reduction in average power to 1.59 watts. No deterioration in reproduction could

be detected by a listening test in the original system with four tubes removed.

At an average power output of 20 milliwatts, a 22-db factor of safety for peaks still remains. If a four-tube system were acceptable (neighbor objection may be anticipated in a single-house residential section where house spacing is on approximately 100-ft centers, if the average level is maintained as high as 50 milliwatts) a supply of 1-ampere capacity would suffice.

A selenium rectifier of the full-wave bridge type could be used to advantage for space economy. One-ampere chokes of approximately 100 millihenrys in a double-pi filter will be more than adequate filtering if used with three 500- μ f capacitors of the proper voltage rating. Proper isolation of the cathode-follower stage and speaker system might allow the rectifier to be supplied directly from the a-c line without power-line transformers.

Four amplifiers using eight tubes have been built and lived up to all expectations. Those who may have requirements for much more power output, such as an auditorium or theater, might consider a 20-tube system. Table I gives an interest-

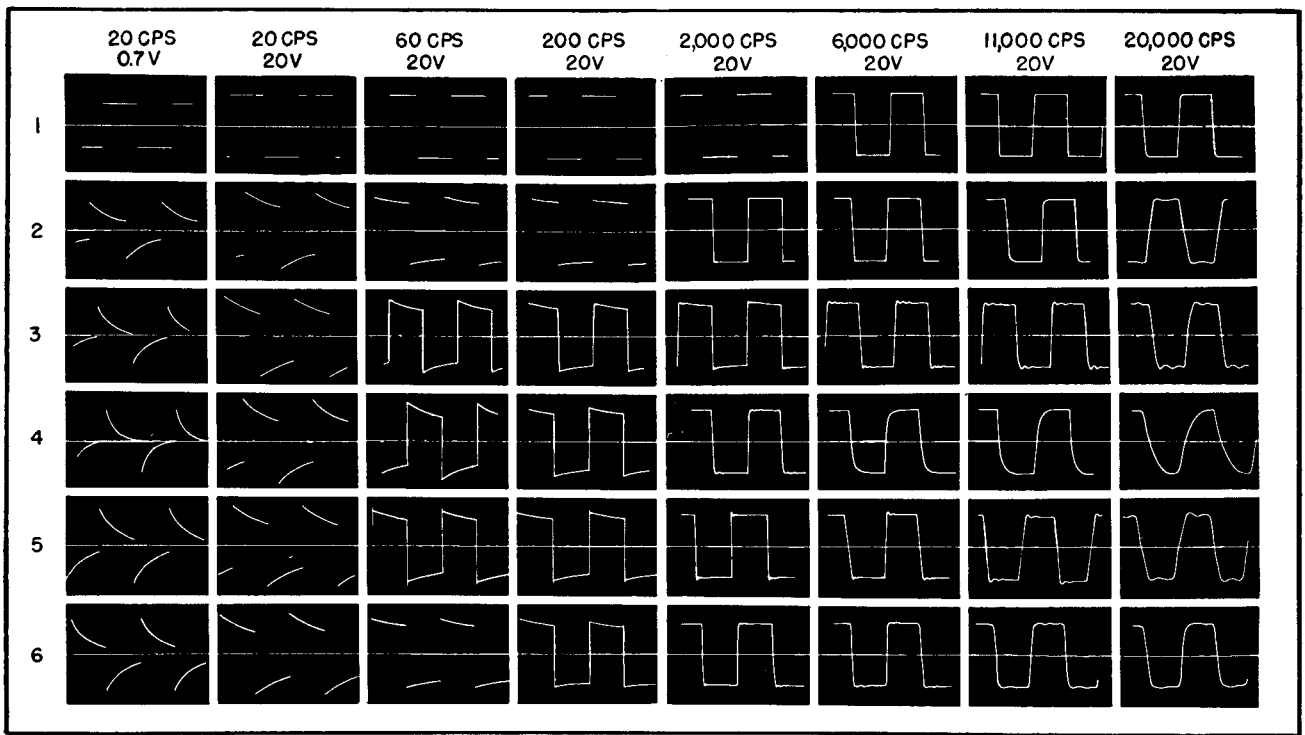


FIG. 5—Square-wave oscillograms obtained in comparison between follower output stage and various high-quality transformers. Top row shows the follower results. Transformer types are listed in the text

ing comparison of cathode-follower output stages, using 4, 8, 12, 16, and 20 tubes.

Highly efficient speakers, not acoustically matched throughout the whole of the audio spectrum, must be well damped electrically. Some advocates propose an effective impedance looking back into the amplifier of a fraction of an ohm, usually accomplished by heavy feedback. Another theory proposes that such electrical damping have a resistance of the order of value of the voice-coil impedance. Whatever may be the better for transformer coupling into an electrodynamic speaker system may be questionable, but no evidence of overshoot can be detected in a Klipsch speaker system driven by the 8-tube cathode-follower stage.

The 15-inch driver is damped properly by virtue of good acoustic matching into the horn. The damping resistance for this case is 19.5 ohms. It is well-known that the speaker impedance is highly variable and the resistive damping afforded by the follower is probably critical when using speakers that have proper acoustic loading. If electrical damping is desirable or necessary, a feedback link from the

voice coil back into the amplifier could be used with no danger of instability or oscillations.

Square-wave tests of five of the best available audio transformers and the eight-tube cathode follower stage exhibited the striking results shown in Fig. 5. The conditions of testing were as follows: Square waves were fed from a balanced generator through resistors equivalent to the plate load of the power tubes driving the transformers. A noninductive resistance load of proper value (16 ohms) was used on the secondary. All transformers and cathode follower were tested under identical conditions. No compensation of any kind was used. Numbers at the left identify the following equipment: (1) cathode follower, 8-6AS7G tubes; (2) General Radio, Special; (3) UTC LS55; (4) Thordarson CHT, 15S91; (5) Partridge, English Williamson amplifier; (6) Peerless S-245-Q.

The first oscillogram in each set was taken with a 20-cps, 0.7-volt input square wave. The second at 20 cps and 20 volts shows the serious effect of the transformers' insufficient inductance. The remaining sets were taken at 60, 200, 600, 2,000, 6,000, 11,000, and 20,000 cps

all with an input voltage of 20 volts.

The authors have used the cathode-follower stage driven by the amplifier in Fig. 3 to feed a good dividing network of less than 0.5-db insertion loss coupled to an 18-in. cone woofer and a metal-diaphragm multicellular tweeter. The reaction after several months of listening to this system might be likened to living with a great painting. At first you are convinced that it is good, but as more live program material is sampled you slowly realize that it is remarkable in its ability to handle extremes of frequency, dynamic range and transients.

In the cathode follower, no problem of leakage inductance nor shunt capacitance exists, therefore, better results at the high frequencies are obtained, especially in the reproduction of percussion instruments. Here steep wave fronts require a frequency response possibly as high as 100 or even 200 kilocycles. Response at the low-frequency end is much better than any transformer available, especially at low power settings. There is an apparent reduction in record scratch while at the same time the high-frequency response is better than with the best transformers.