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A Television Booster Amplifier

Part 1, Design

By the Engineering Department, Aerovox Corporation

THE performance of a television receiver can usually be improved by the addition of a properly designed "booster" or pre-amplifier. This is especially true of one operating on the "fringe" of the transmitter service area where the signal is weak. The "rural coverage area" is defined by the F. C. C. as being the region in which the transmitter signal strength is 500 microvolts per meter or more. In areas where the atmospheric and man-made noise level is low, good reception may be had with much lower signal strengths. Since few of the commercial medium- and low-priced television sets have more than one stage of r. f. amplification preceding the mixer, due to the complexity of gang-tuning additional circuits, the advantages to be gained by adding a high-performance "outboard" r. f. amplifier may include:

a. Improved signal-to-noise ratio.
b. Added gain.
c. Better image rejection.
d. More isolation against local-oscillator radiation.

This paper discusses the principles to be considered in the design of such an amplifier. Part II will detail the construction.

As is quite well known, the sensitivity performance of any radio receiver is largely determined by the characteristics of the first stage. This input circuit establishes the signal-to-noise ratio of the receiver and thus ultimately determines the limit of detectability of weak signals. If the first stage (and more particularly the input circuit) contributes noise voltages due to thermal agitation and tube shot-noise effects which are comparable in magnitude to the received signal voltage, both signal and noise voltages will be amplified equally by subsequent stages. Therefore, a more important consideration than extremely high gain in the first circuit is it's noise characteristic. Of course the input circuit must provide as much gain as is consistent with low noise contribution. If it does not appreciably raise the level of weak signals, then the noise figure of the second stage assumes importance.

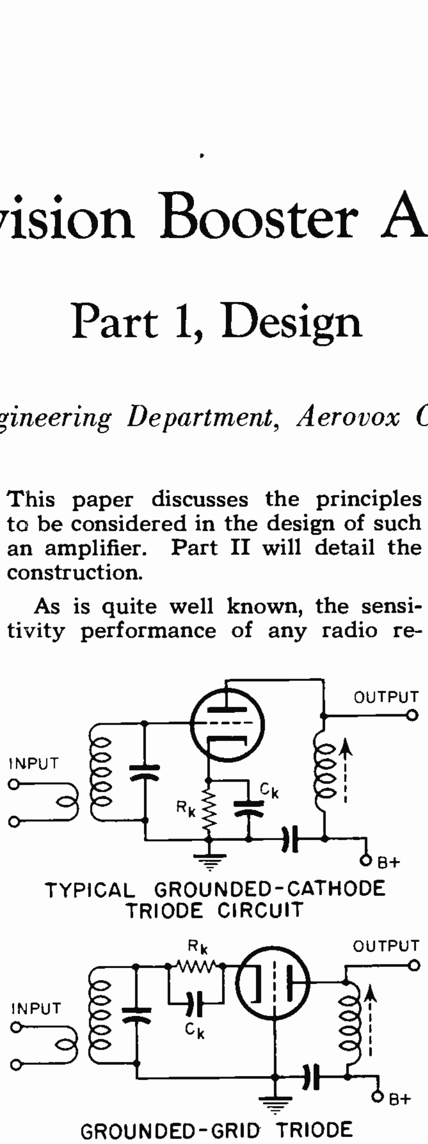


FIG. 1

The design of the receiver input stage thus becomes a problem of finding a suitable compromise between low noise performance and amplification. Since the booster amplifier is to become the all-important input stage of the television receiver, a satisfactory solution to this problem must be found in it's design.

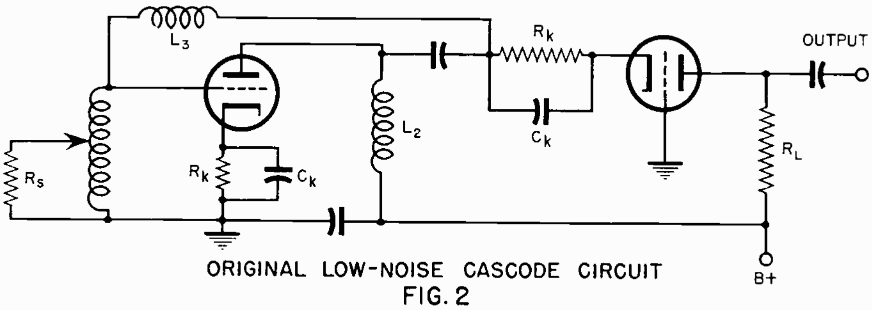
Comparison of Tube Types

In selecting a tube compliment for an r.f. pre-amplifier, the designer is invariably attracted by the low noise characteristics of the triodes. Pentode tubes contribute noise currents which are several times greater than those of triodes or triode-connected pentodes. This is because the random division of cathode current between the screen and plate elements of a pentode is a source of noise (called "partition noise") just as the random fluctuations in cathode current in any tube is a source of noise. The "noise figure of merit" of a vacuum tube is expressed as it's *equivalent noise resistance*, i.e., the value of the actual resistor which would generate an equal noise level. Tubes with low equivalent resistance values generate the least noise. The values range from 210 ohms for the 6J4 triode to over 1800 ohms for the 6AK5 pentode. A 6AK5 connected as a triode has an equivalent noise resistance of only 385 ohms.

When used in broad band circuits, where the loading resistances are of necessity quite low, the triode is also capable of gains comparable to those achieved by pentodes. This is because the much higher internal resistance of the pentode dissipates much of it's available power within the tube when it is used with heavily loaded (low resistance) output circuits.

Circuit Types

For these reasons, the triode would seem a very logical choice for use in a television pre-amplifier. When used in the conventional grounded-cathode circuit as shown in Fig. 1, the triode has one serious disadvantage, however. The higher plate-to-cathode capacitance provides feed-back which causes instability in the form of oscillation when an attempt is made to use the triode at high gain. Neutralization or special circuit configurations may be used to reduce this tendency. A triode connected as a grounded-grid amplifier as shown in Fig. 1 is very stable since the grid is at r. f. ground potential and acts as an electrostatic shield between the input and output circuits. The available gain is much less than that obtainable from the grounded-cathode circuit, however, since a degenerative effect takes place in the cathode circuit. A signal voltage which tends to make the cathode more negative with respect to the grounded-grid, and thus increase the plate current, is opposed since the increased plate current flows through the cathode resistor in such a direction as to make the cathode *less* negative. This effect reduces the gain and the sensitivity to weak signals.



ORIGINAL LOW-NOISE CASCODE CIRCUIT
FIG. 2

The input resistance of the grounded-grid amplifier is also very low compared with the grid input circuit. In a grounded-grid stage where the plate circuit is heavily loaded to achieve greater bandwidth, as would be the case in a television booster, the input resistance is approximately equal to the reciprocal of the tube transconductance expressed in ohms. Thus, a tube with a transconductance of 3300 microhms (.0033 ohms) would have an input resistance of roughly 1/.0033 or 300 ohms. This low value of resistance shunted across a tuned input circuit would cause it to be quite broad — about 50 megacycles — and hence would make tuning unnecessary. This low input resistance feature of the grounded-grid amplifier is used in several commercial television sets to directly match the 300 ohm twin-lead transmission line from the antenna. In a booster amplifier, such "wide open" input circuit tuning is considered to be detrimental since it provides no discrimination against off-channel, spurious signals and external noise.

Therefore, if restricted to a single triode, the designer has a choice between the high gain grounded-cathode circuit with it's inherent tendency toward oscillation, and the highly stable grounded-grid circuit with it's lower gain and much less selective input circuit. As far as noise figure is concerned, there is little difference between the two circuits, although the lower gain of the grounded-grid arrangement may make the noise contribution of the following stage assume some importance.

The Cascode Circuit

The ideal solution would, of course, be a circuit combining the desirable features of both types discussed above, with the disadvantages of each eliminated. Such a high-gain, low-noise, stable circuit arrangement does indeed exist in the special "cascode" amplifier which was developed by Wallman, Macnee and Gadsden* at the M. I. T. Radiation Laboratory in 1944 and widely used as an intermediate amplifier input circuit for radar receivers. The design described here is an adaptation of this circuit for use as a high-performance television pre-selector.

The basic circuit of the cascode amplifier is shown in Fig. 2. Two tubes are used; a grounded-cathode triode followed by a grounded-grid triode. The two triodes (or triode-connected pentodes) used in this combination give a gain only slightly better than that obtainable from a single typical pentode. However, a considerable improvement in the noise figure is realized. When dealing with low signal levels, any improvement in this direction is of importance, especially when it is considered that an increase of 3 db. in the signal-to-noise ratio of a receiver is the equivalent of doubling the transmitter power or reducing the effective distance to the transmitter by about 16%.

The cascode derives it's good noise figure (the best obtainable at the present state of the art) from the fact that, beside being low noise triodes, both tubes are driven from source resistances which are adjusted to give minimum noise. It has been demonstrated that the noise performance of a vacuum tube amplifier can be markedly improved by over-coupling the input circuit to it's driving source. An optimum degree of over-coupling exists at which the reduction in noise more than compensates for the decrease in gain occasioned by the mismatch. A net improvement in the signal-to-noise ratio results. The resistance which is presented to the amplifier grid at this optimum coupling is called the "optimum source resistance."

The cascode amplifier is non-critical to adjust and exhibits a high degree of

*Henry Wallman, Alan B. Macnee and C. P. Gadsden, "A Low-Noise Amplifier" Proc. I. R. E., June 1948.

stability. This stability is achieved in the inherently instable grounded-cathode stage by loading it heavily with the low input resistance of the grounded-grid stage so that oscillation does not occur. At the same time, the plate resistance of the first stage is roughly the optimum source resistance of the grounded-grid stage. A neutralizing coil (L3) is shown in Fig. 2 which contributes to the stability of the circuit, but is used principally because it effects a reduction in the noise figure.

Thus, with it's desirable combination of characteristics as outlined above, the cascode circuit offers an ideal approach to the problem of a practical television booster. Let us now examine the modifications necessary to adapt it to that application.

In addition to being tunable to each of the channels to be received, the booster amplifier must have a band-pass at least equal to the 6 megacycle width of each television channel. The type of response curve generally accepted as standard for television r. f. front-ends is shown in Fig. 3. This bandwidth is not difficult to obtain at frequencies in the television spectrum since the loading effect of the tubes used is appreciable. The band-pass achieved is also greatly influenced by the type of tuning circuits used. (See RESEARCH WORKER, January, 1949.)

The problem of tuning the cascode circuit is somewhat simplified by the fact that it is not necessary to tune the interstage coupling. Due to the heavy loading of the grounded-grid stage, as explained above, this coupling may be made broad enough for all practical purposes. As an example, if a tube such as the 6J4 with a transconductance of 12,000 is used for the second tube, the interstage coupling is loaded by the grounded-grid input resistance of only about 86 ohms. At this loading, the bandwidth of the "tuned" circuit at the 3 db. points approaches 200 megacycles. Thus, variable tuning need only be accomplished in the input circuit of the first tube and the output circuit of the second tube.

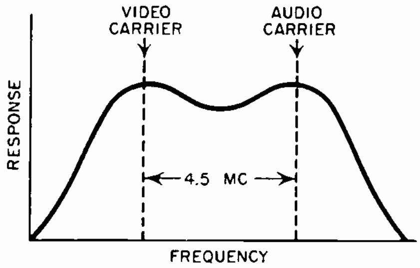


FIG. 3

Considerable care must be exercised in the design of the input circuit. Several conditions must be satisfied for optimum performance. They include; (1) The antenna coupling should be of the balanced type, or at least semi-balanced, since balanced 300 ohm twin-lead is standard in television practice. (2) Broadbanding should be accomplished by means other than the addition of physical "loading" resistors, because such resistors in this low-level circuit would contribute excessive thermal noise. (3) The antenna impedance should be transformed by the input circuit to a value close to the optimum source resistance of the first tube. (4) Capacity tuning should be avoided unless it is desired to reduce the bandwidth of the circuit. (5) A voltage step-up should be effected if possible.

These requirements are most easily met by the use of a semi-balanced transformer coupling between the transmission line and the grid of the first tube. Conditions (2) and (3) above are fulfilled by adjusting the turns ratio of the input transformer for optimum noise rather than perfect impedance match. The overcoupling required by this condition also broadens the response of the circuit appreciably.

Since the optimum source resistance varies inversely with frequency, the turns ratio of the input transformer cannot remain constant throughout the television band, but must be varied so as to transform the antenna resistance to the optimum source resistance at the tube grid. For the 6AK5 tube used as a triode, the optimum source resistance is approximately equal to the constant 70500 divided by the operating frequency in megacycles. From this it is seen that optimum driving resistance varies from about 1400 at 50 megacycles, to only slightly greater than 350 ohms at 200 megacycles. The turns ratio to effect the necessary transformation can be computed from the familiar equasion:

$$(1) \qquad k\frac{N_s}{N_p} = \sqrt{\frac{R_{opt}}{R_{ant}}}$$

Where:

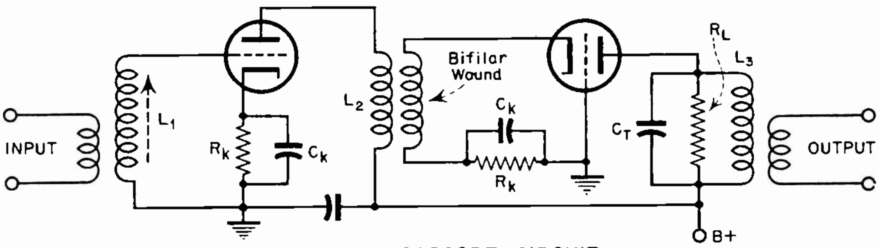
N_s = Number of secondory turns
N_p = Number of primory turns
R_{opt} = Optimum source resistonce
R_{ant} = Antenno resistonce
k = Coefficient of coupling

The adjustment of turns ratio with frequency can best be accomplished by switching input transformers by means of a standard rotary wafer switch. This also allows for pruning or slug-tuning each input coil to resonate with only the tube and circuit capacity so that condenser tuning may be eliminated. Channel selection is simplified by the fact that a separate input circuit is not needed for each channel to be received. Tube loading and the necessary over-coupling broaden the input circuit so that two or more channels may be "doubled-up" on each switch position if necessary for simplicity.

In the interstage coupling circuit, the neutralizing coil L3 may be eliminated without serious effects, since it would require tuning. To provide a d. c. path for the cathode current of the grounded-grid stage, L2 may be bifilar wound by twisting two wires together and winding them on a form as one wire. The resulting unity-coupled transformer carries both the plate current for the first stage and the total cathode current for the second stage. The bifilar winding, appearing as a single inductance, is resonated with the tube and circuit capacitance at mid-band.

In the output circuit, conventional variable capacity tuning may be used for simplicity. Loading resistance is used to increase the bandwidth of this circuit without serious degradation of the noise performance of the booster since the signal has been considerably raised above the noise level by the gain of the preceding stages.

Fig. 4 shows the cascode circuit as modified for use as a television booster in accordance with this general discussion. The AEROVOX RESEARCH WORKER for April will describe in detail the construction of an experimental booster using these principles.



MODIFIED CASCODE CIRCUIT
FIG. 4

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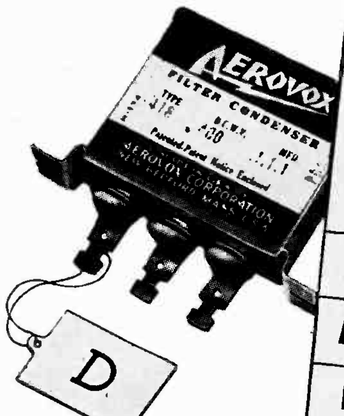

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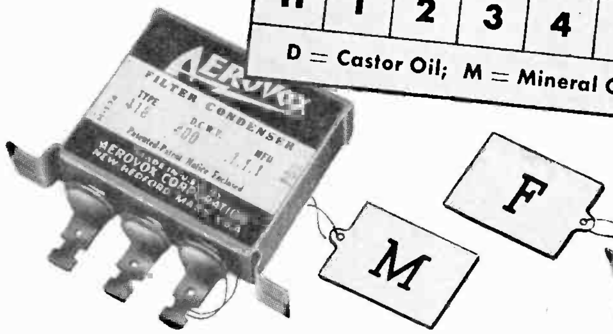
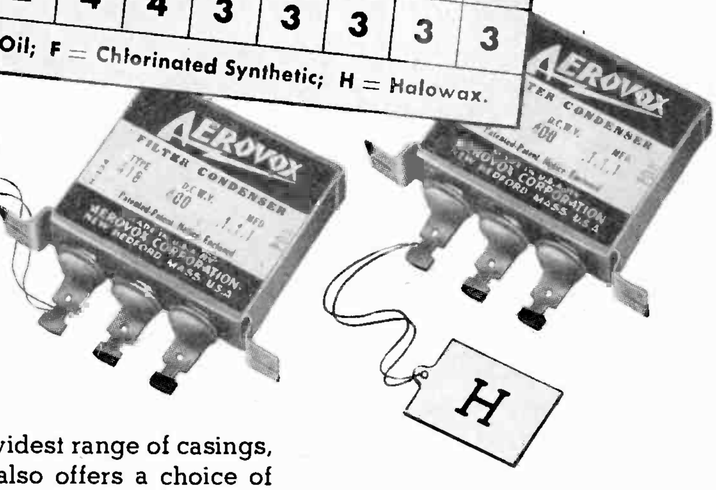
Numerals indicate impregnants in their order of preference

Impregnant	Size	Weight	Insulation Resistance	Power Factor	Cap. variation with temperature	High temperature operation	Low temperature operation	A. C. operation	D. C. operation	High voltage A. C. operation	High voltage D. C. operation	High frequency operation
D	2	1	4	3	2	3	2	2	2	2	1	2
M	3	4	1	1	1	1	1	1	1	1	1	1
F	2	3	2	2	3	2	3	1	4	1	2	2
H	1	2	3	4	2	4	4	3	3	3	3	3

D = Castor Oil; M = Mineral Oil; F = Chlorinated Synthetic; H = Halowax.





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