A NOTE ON NOISE IN AUDIO AMPLIFIERS*

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The limitations of background noise present a universal problem to designers of high-gain amplifiers. This technical editorial was invited for the purpose of summarizing these limitations for readers of TRANSACTIONS of the IRE-PGA. It happens that the conclusions are not in complete accord with another paper in this same issue.** The papers are being published simultaneously so that readers may have the benefit of both points of view.

— Editorial Committee

There are a number of noise sources in audio amplifiers such as:

a. Thermal noise in the input coupling circuit
b. Shot noise
c. Partition noise in pentodes
d. Flicker noise
e. Ballistics and microphonics
f. Pops
g. Hum

Hum will not be considered here although it is a serious problem and much can be said concerning its elimination. Ballistics, microphonics, and pops are matters of tube design and selection rather than circuit design and will not be considered either.

This paper will be primarily concerned with flicker, shot, and partition noise and the effects of the input coupling network. An attempt will be made to outline the requirements of the input circuit and to discuss the magnitude of second stage noise in conventional configurations.

Noise is generated in the resistive component of any impedance by the thermal agitation of the electrons. The magnitude of the thermal noise voltage of a resistance in temperature equilibrium is:

$$e = \sqrt{4kTBR} \text{ volts rms}$$

where

k = Boltzmann's constant
T = temperature in degrees Kelvin
R = resistance in ohms
B = bandwidth in cycles per second

A certain signal-to-noise ratio is available from the source and is determined by the signal strength and the magnitude of thermal noise. Using an amplifier, it can be approached but never exceeded. Noise figure is a convenient way of expressing the amount by which an amplifier deteriorates the signal-to-noise ratio available from the source. Noise figure may be defined as the available signal-to-noise ratio at the source divided by the available signal-to-noise ratio at the amplifier output. An equivalent definition is that noise figure is the ratio of the total noise power at the output of the amplifier to that component of the noise output power which is due to thermal noise in the source impedance. Noise figure is costumarily expressed in db.

Shot noise is generated because the plate current of a tube is not continuous, but consists of discrete charges which are numerous enough to very closely approximate a continuous current. Partition noise in pentodes is similar to shot noise but is caused by the division of current between the plate and the screen. Flicker noise is caused by local fluctuations of emissivity of the cathode. These sources of noise may be lumped and their effect duplicated by an equivalent voltage generator. This generator is commonly represented by a resistor, R_{eq}, in series with the grid of the tube and is chosen to be of such a value that the thermal noise voltage generated by it is equal to the sum of the shot, partition, and flicker noise voltages referred to the grid circuit. Thus:

$$R_{eq} = R_{shot} + R_{part.} + R_{flicker}$$

Shot noise and partition noise are independent of frequency and their equivalent noise resistances are generally considered to be:

$$R_{shot} = \frac{2.5}{g_m}$$

$$R_{part.} = \frac{20\, I_{screen}}{g_m\, I_{cathode}}$$

In the audio frequency band, flicker noise is much greater than either of the above two noise sources. It is a function of frequency and thus its equivalent noise resistance, $R_{flicker}$, is also. For any particular frequency characteristic an integrated $R_{flicker}$ can be found that is a constant.

The noise spectrum of a typical low noise triode with a coated cathode is shown in Fig. 1. In this tube, R_{shot} is 1500 ohms and $R_{flicker}$ integrated over a 12 kc flat bandwidth is 6000 ohms.

Consider the problem of determining the noise figure of an audio amplifier stage. Identical grounded-grid and grounded-cathode triodes with the same source re-

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**R. Lee Price, "The Cascode as a low noise audio amplifier."

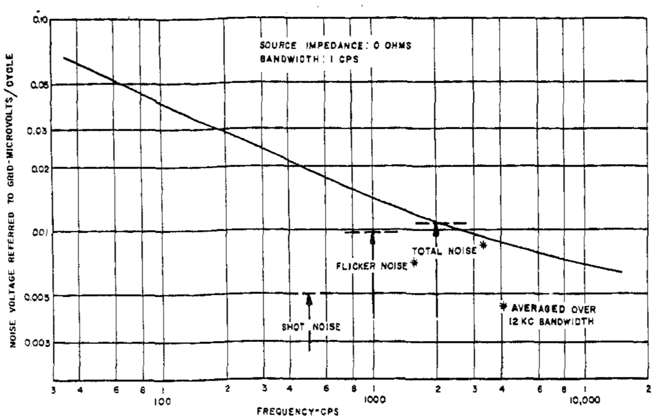

Fig. 1 – Triode tube noise vs. frequency.

sistance, R, are shown in Figs. 2 and 3. The tube noise is referred to the grid circuit and is represented by R_{eq}, which is a fictitious generator of voltage $e = \sqrt{4kTBR_{eq}}$. The tubes are then considered to be ideal amplifying devices. Since noise figure is:

$$F = \frac{\text{total noise power at the output}}{\text{that component of output noise due to thermal noise in the source}}$$

$$= \frac{4kTBR_s + 4kTBR_{eq}}{4kTBR_s} = 1 + \frac{R_{eq}}{R_s}$$

The interesting fact is that the noise figures of the grounded-cathode and grounded-grid stages are identical. Thus, although the input resistance of a grounded-grid stage might be under 500 ohms, a high source resistance

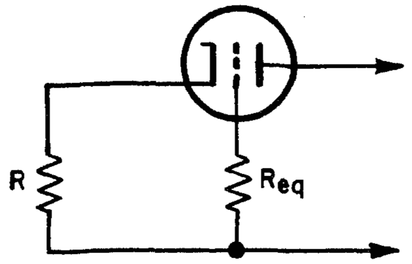

Fig. 2 – Grounded-grid equivalent circuit.

of perhaps 30,000 ohms is required to obtain a good noise figure just as in the case of the grounded-cathode connection.

It is to be noted that the above expressions represent *first* stage noise figures. The noise figure of an amplifier represents the deterioration of signal to noise ratio by *all* the stages in the amplifier. If the first stage gain is high, the succeeding stages do not contribute appreciable noise and the noise figure of the amplifier is about the same as that of the first stage. This is generally the case in audio amplifiers.

On the other hand, an amplifier with a grounded-grid input tube must be operated from a low source resistance to obtain appreciable first stage gain. Hence this amplifier is either operated from a high resistance source and suffers from noise contributed by the second stage, or is operated from a low resistance source and has a poor first stage noise figure, or some combination of the two.

Excepting ballistics, microphonics, hum, and pops, the following general conclusions can be drawn:

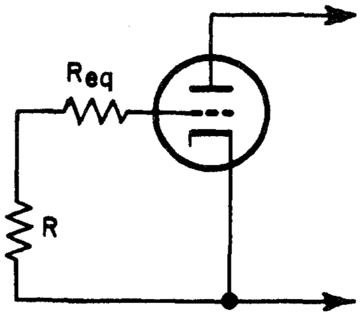

Fig. 3 – Grounded-cathode equivalent circuit.

Noise figure improves as the source impedance increases and zero db. noise figure can be approached in practice. (A low-noise triode with 22,000 ohm source resistance has a 1.0 db noise figure. See Fig. 4). As a result, efficient input transformers greatly improve the noise figure of a system with a low impedance source such as magnetic pickups and microphones.

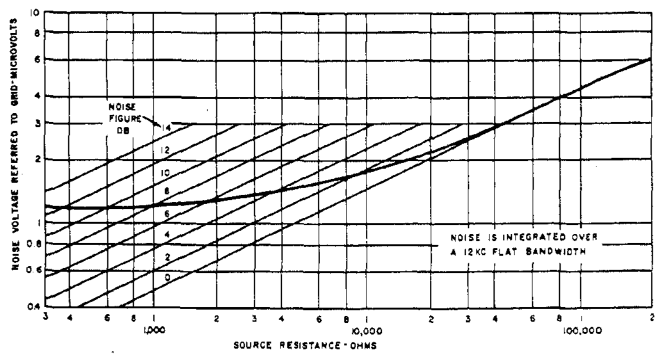

Fig. 4 – Noise vs. source resistance.

If the source impedance is low and bandwidth requirements or other conditions permit, the noise figure can be improved by paralleling input tubes increasing the g_m and thereby lowering R_{eq}.

It is to be noted that noise figure, *per se*, is meaningless. To express the performance of an amplifier, one must specify the noise figure with a given source resistance.

The noise figure of a stage is independent of the configuration, i.e., whether the stage is grounded-cathode or grounded-grid. Generally the gain of the first stage is high enough so that second and later stage noise make only a small contribution to the total.

Thus it can be generalized that cascaded grounded cathode stages at audio frequencies will give as good or better noise performance than other possible circuit configurations. In addition this configuration is most advantageous from a practical point of view – such as heater B+ supplies.

APPENDIX

A typical amplifier employing two cascaded grounded cathode stages is shown in Fig. 5. R_s and L_s are respectively the series resistance and inductance of

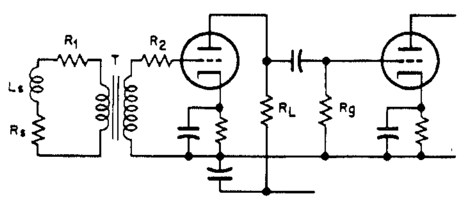

Fig. 5 – Typical two-stage amplifier.

the source. T is an input transformer with a turns ratio of n, a primary resistance of R_1, and a secondary resistance of R_2.

The equivalent circuit is shown in Fig. 6 where

$$L = n^2 L_s$$

$$R = n^2 R_s$$

$$R_t = n^2 R_1 + R_2$$

$$R_i = \frac{R_g R_L}{R_g + R_L}$$

The equivalent noise resistors of the two stages are represented by R_{eq^1} and R_{eq^2} respectively.

Examination of the noise figure of this amplifier will be made at point A. The noise figure at the input of the first ideal tube is:

$$F_1 = \frac{4kTB(R + R_t + R_{eq1})}{4KTBR} = 1 + \frac{R_t}{R} + \frac{R_{eq1}}{R}$$

The noise voltage due to the interstage coupling circuitry and the second tube is:

$$E_i = \sqrt{4kTB}\sqrt{\left(\sqrt{R_i}\,\frac{R_p}{R_p + R_i}\right)^2 + \left(\sqrt{R_{eq^2}}\right)^2}$$

$$= \sqrt{4kTB}\sqrt{\frac{R_i}{\left(1 + \frac{R_i}{R_p}\right)^2} + R_{eq^2}}$$

where R_p is the plate resistance of the first tube. Dividing the above expression by the first stage voltage gain, G, this noise voltage is referred to the amplifier input so that the ratio of the ideal to actual noise powers due to the source and due to the interstage circuitry is:

$$F_2 = \frac{\dfrac{R_i}{\left(1 + \dfrac{R_i}{R_p}\right)^2} + R_{eq^2}}{G^2 R_s}$$

The over-all noise figure of the two stages up to point A is then:

$$F = F_1 + F_2 = 1 + \frac{R_t}{R} + \frac{R_{eq^1}}{R} + \frac{1}{G^2}\,\frac{\dfrac{R_i}{\left(1 + \dfrac{R_i}{R_p}\right)^2} + R_{eq^2}}{R}$$

The above formula might be construed to mean that it would be desirable to let the source impedance have as high a resistive component as possible. However, an increase in source resistance must be accompanied by a corresponding increase in signal voltage, as is realized with an input transformer or with a "high impedance" magnetic playback head.

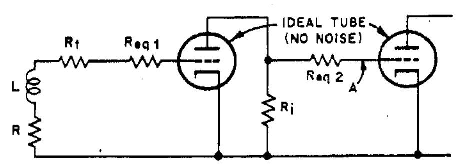

Fig. 6 – Equivalent circuit of two-stage amplifier.

A typical amplifier using a 12AY7 twin triode might have the following constants:

n = 28.3
L_s = 2 mh
R_s = 1 ohm
R_1 = 8 ohms
R_2 = 6000 ohms

$$R_{shot}\,1 = R_{shot}\,2 = \frac{2.5}{1660 \times 10^{-6}} = 1500 \text{ ohms}$$

$R_{flicker}1 = R_{flicker}\,2$ = 6000 ohms
R_L = 100,000, R_g = 1,000,000 } R_i = 100,000 ohms
R_p = 25,000 ohms
G = 30

then:

$R_{eq^1} = R_{eq^2}$ = 7500 ohms
n^2 = 800
L = 1.6 hy
R = 800 ohms
R_t = 12,400 ohms

and

$$F = 1 + 15.5 + 9.4 + 0.02 = 25.9$$

or an equivalent ratio of 14.1 db.

From the above example it can be seen that the noise in this system is over 14 db worse than that which could have been obtained with an ideal amplifying device. A substantial noise contribution is made by the resistance in the input transformer, yet a negligible amount is contributed by the interstage coupling network and the second tube.

A preferred arrangement that would eliminate the noise contribution of the input transformer could be obtained by the use of a "high impedance" head. Thus:

$$n = 1$$
$$L_s = L = 1.6 \text{ hy}$$
$$R_s = R = 800 \text{ ohms}$$
$$R_1 = R_2 = R_t = 0 \text{ ohms}$$

other values as above.

Under these conditions

$$F = 1 + 9.4 + 0.02 = 10.4$$

or an equivalent ratio of 10.2 db.

Even here, the second stage noise contribution is negligibly small.

HOUSTON PGA CHAPTER

L. A. Geddes, Chairman

On Thursday, December 10, 1953, the Houston Chapter of the Professional Group on Audio held its second meeting of the season at the Haliburton Oil Well Company Auditorium in Houston, Texas. The meeting was well attended. Only standing room was available after 8:30 P.M. The attendance was made up of 6 PGA members, 12 IRE members, and 42 guests.

The program commenced with a sound film on the manufacture and testing of magnetic tape. The process described in the film was that used by Audio Devices Inc., of New York. It is similar to the production processes carried out by other manufacturers.

Following the film, a talk, "Binaural Sound Principles and Practices," was given by Harry Keep of Gulf Coast Electronics Company. The requirements of the system were outlined and was followed by a description of recording and playback equipment. A short summary of the present status of the art and the possibilities of binaural reproduction for home use, was also given.

A demonstration recording of a ping-pong game on binaural tape was reproduced through a Magnecord Recorder, McIntosh Amplifier, and two Bozak Loudspeaker Enclosures. The tape ably illustrated the principles and listening possibilities inherent in the Binaural System.

The latest Emory Cook "Sounds of our Times" twin track disc recordings were then played through the system. The level of the two Binaural Channels was altered from *zero* to *maximum* to illustrate the illusion of presence and spatial distribution obtained with this method of reproduction.

The meeting formally adjourned at 10:30 P.M. and was followed by an informal session of more recorded music on an experimental *Request-from-the-Audience* basis.

HOW MUCH DISTORTION CAN YOU HEAR?

E. M. Jones, Chairman
Cincinnati Chapter IRE-PGA

"How Much Distortion Can You Hear?" was the subject of the November 17, 1953 meeting of the Cincinnati Chapter IRE-PGA. A specially prepared series of recorded tones was played as a demonstration test of percentages of harmonic and intermodulation distortion which can be detected. The preparation of the tape recording was a cooperative effort of the executive committee consisting of E. M. Jones, The Baldwin Company; W. W. Gulden, Cincinnati and Suburban Telephone Company; J. Parke Goode, National Sound Service. They were assisted by D. W. Martin of The Baldwin Company. The demonstration also included several live A-B comparisons from the oscillators and the distorting amplifier which had been used to make the tape.

The test series consisted of 15 different sample tones having known harmonic or intermodulation distortion compared with "undistorted" signals. In each case the distorted signal and "undistorted" signal were presented five successive times in randomized paired comparisons. For each time, the listener was asked to choose whether the "undistorted" signal came first or second. The percentage distortion and the correct answers were announced after each group of five comparisons.

The test tones were sinusoidal signals of ap