Limits to Amplification *

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The amplification obtainable in a vacuum tube amplifier is limited by the noise in the circuit. Of the various sources of noise the most fundamental and inevitable is thermal agitation of electricity. Other sources are the influence of ions and of shot effect and flicker effect on the current in vacuum tubes, poor contacts, mechanical vibration, and hum from a.-c. cathode heating. These noises and their effects in limiting amplification are discussed in this paper. Although the natural noise level of an amplifier is exceedingly low, modern amplifiers have reached such a stage of perfection that their noise levels often are practically at the natural limit.

NOISE in amplifiers is now a familiar term. Any one who has had his favorite radio hour ruined by static knows the effect of an incoherent background of noise. Although static was one of the first noises observed in radio amplifiers, its origin is really outside the circuits. At one time it seemed that other sources of noise of purely local origin, such as poor batteries, loose contacts, gassy tubes and induction from power lines, might be eliminated entirely so that the circuits would be capable of amplifying any signal, no matter how small. It was found, however, that the noise level cannot be lowered indefinitely; that there are limits below which, in the nature of things, noise cannot be reduced.

Of the sources of noise, the most fundamental and inevitable is thermal agitation of electricity. In a perfect amplifier all other noises would be reduced to a level below that of thermal agitation. Next in order comes the influence of ions and of shot effect and flicker effect on the current in the vacuum tubes. Under control to a greater extent, but nevertheless of a malignant nature, are the effects of poor contacts, mechanical vibration, and hum from a.-c. cathode heating. In dealing with these disturbances, the circuit and vacuum tube of the first stage of the amplifier are the most important, for here the signal being amplified is at its lowest level. When the signal is so faint that it is masked by the noise remaining as the natural limit of the circuit, then the only possible remedy is to raise the signal level.

The natural noise level is exceedingly low, yet modern amplifiers have reached such a stage of perfection that their noise levels often are practically at the natural limit. This is true not only of special amplifiers built for experimental purposes, but of many amplifiers

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* Published in November 1934 issue of *Electrical Engineering*. Scheduled for presentation at Winter Convention of *A. I. E. E.*, New York City, January 22–25, 1935

used in commercial circuits. The natural limits to amplification which will be discussed in this review are therefore of very practical interest.

THERMAL AGITATION[1, 2, 3, 4, 5, 6]

The free charge of any conductor is in random motion in equilibrium with the thermal motion of the molecules of the conductor and this flow of charge creates a random voltage across the terminals of the conductor. This voltage usually is observed in a system composed of an amplifier with an input circuit and an output device. Its mean-square value across the output device is given by the expression

$$V_{to}^2 = 4kT \int_0^\infty RG^2 df, \tag{1}$$

where the symbols have the following meanings:

k is the Boltzmann gas constant and is equal to 1.37×10^{-23} watt-second per degree,
T represents absolute temperature, degrees Kelvin,
R represents the resistive component in ohms of the input impedance as measured across the input terminals of the amplifier,
G represents the voltage gain of the amplifier, and is equal to the ratio of voltage across the output device to voltage across the input terminals of the amplifier,
f represents frequency in cycles per second,
R and G are in general functions of frequency.

In the simple case where the amplifier has a constant gain over a frequency range F and no gain outside of this range, and where R is also constant over the same frequency range and is at the normal temperature of 300 degrees, the mean-square noise voltage across the input terminals of the amplifier is

$$V_t^2 = 1.64 \times 10^{-20} RF. \tag{2}$$

This is the voltage that would be produced by a generator supplying to the resistance R the power

$$W = \frac{V_t^2}{R} = 1.64 \times 10^{-20} F. \tag{3}$$

The power W, sometimes expressed as 1.64×10^{-20} watts per cycle, is independent of R and may be regarded as the apparent input power of the thermal agitation. It depends only on the frequency range of the amplifier, since the temperature cannot be varied conveniently or

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[1] For all numbered references see bibliography at end of paper.

very effectively and it sets a lower limit to the possibility of amplifying electrical impulses of any kind. Any signal much smaller than the thermal noise would be masked hopelessly. The only factor under control in the noise equation is the frequency range F, which should be no greater than is needed for the transmission of the signal.

An example will illustrate the magnitude involved in this limit to amplification. When the signal is speech requiring a frequency band of 6,000 cycles, then the apparent power generated at the input of the amplifier by thermal agitation is 0.985×10^{-16} watts, which is about 138 db below the common reference level of 0.006 watts. (The level of 10^{-16} instead of 0.006 watts is being considered as a reference point for the decibel scale in communication circuits. This is approximately the level of thermal noise in a 6,000-cycle channel.) If the input resistance were one megohm the corresponding r.m.s. noise voltage would be 9.94 μv.

A signal represents a certain amount of available power, and when this is so small that it is near the thermal noise level it must be used efficiently to produce voltage at the grid of the amplifier tube.[7, 8] Let the signal be supplied by a generator of voltage E and internal resistance R_1 which delivers power to a load resistance R_2, the combination forming the input circuit of the amplifier as shown in Fig. 1. The mean-square signal voltage on the grid of the amplifier tube is

$$V_{sg}^2 = \frac{E^2}{R_1^2}\left(\frac{R_1R_2}{R_1 + R_2}\right)^2. \tag{4}$$

However, the resistance required by equation 2 for the noise is the combination of R_1 and R_2 in parallel, so that the mean-square noise voltage on the grid of the amplifier tube is, from equations 2 and 3

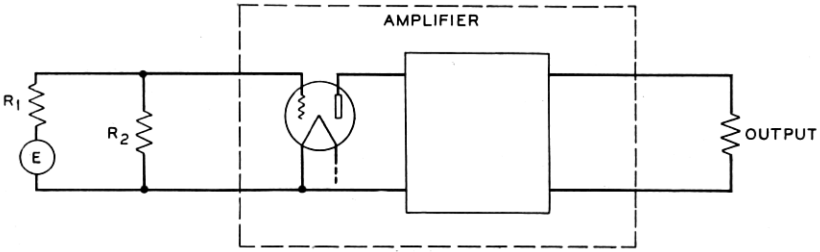

Fig. 1—Schematic diagram of a vacuum tube amplifier showing equivalent input circuit.

$$V_n^2 = WR = W\left(\frac{R_1R_2}{R_1 + R_2}\right). \tag{5}$$

Hence the signal-to-noise ratio is

$$\frac{\boldsymbol{V}_{sg}{}^2}{\boldsymbol{V}_n{}^2} = \frac{\boldsymbol{E}^2}{WR_1}\left(\frac{R_2}{R_1 + R_2}\right). \tag{6}$$

In general, the internal resistance R_1 of the signal generator is fixed, so that R_2 is the only available variable. In the usual case of matched impedances where R_1 and R_2 are equal, the signal-to-noise ratio is 3 db poorer than in the ideal case where R_2 is made very large compared with R_1. This is one of the few examples where a mismatch of impedances is advantageous. The use of an ideal step-up transformer between R_1 and R_2 in Fig. 1 will be of no avail, so far as the thermal noise is concerned, because its effect in equation 6 will be only to replace R_2 by R_2/N^2 where N is the turns ratio of the transformer.

In some systems the impedance at the input of the amplifier is unavoidably small. It may be so small that the voltage of the thermal agitation of the input circuit, even when amplified by the first tube, is lower than the noise voltage originating in the output circuit of that tube. Ideally, the noise in the plate circuit also should be caused by thermal agitation only, and the equations for it have been derived.[9, 10] In practice, however, the noise in the plate circuit is found to be considerably greater, for reasons that will be discussed presently.

SHOT EFFECT AND FLICKER EFFECT WITHOUT SPACE CHARGE

Early in the study of noise arising in vacuum tubes it was shown [1, 11] that under certain conditions a noise is produced that depends on the fact that the electric current is a flow of discrete particles, the electrons, which are emitted from the cathode in a random manner. The random electron emission produces a statistical fluctuation in the current that flows through the tube and coupling impedance. This fluctuation, called the shot effect (German Schroteffekt, in analogy with the random scattering of shot from a shot gun), appears as noise in the output of the amplifier. When the current in the tube is limited by the rate of emission of electrons rather than by the space charge, so that the resistance of the tube is nearly infinite, then the shot effect produces a mean-square voltage across the output impedance of the amplifier given by [12, 9]

$$V_{so}{}^2 = 2\epsilon i \int_0^\infty Z^2 G^2 df, \tag{7}$$

in which

ϵ represents the charge on the electron and is equal to 1.59×10^{-19} coulomb,

i represents space current in amperes,
Z represents the magnitude in ohms of the coupling impedance,
G represents the voltage gain of the amplifier from Z to the output,
f represents frequency in cycles per second,

For an amplifier having a flat frequency response curve over frequency range F the expression becomes, for the effective shot noise across the impedance Z

$$V_s^2 = 31.8 \times 10^{-20} i Z^2 F. \tag{8}$$

The expression holds quite accurately for tubes in which the cathode is made of either clean or thoriated tungsten and for high-vacuum photo-electric tubes, and it has been used in determining the charge on the electron.[13]

When an oxide coated cathode is used, fluctuations of a larger magnitude [14] are superimposed on the true shot effect. These fluctuations are inappreciable above about 10 k.c., but increase rapidly in magnitude toward the lower frequencies. They also increase with the current at a faster rate than the shot effect fluctuations. This disturbance has been ascribed to a state of flux and change in the activating material on the surface of the cathode,[14, 15] and the phenomenon has been called the "flicker effect" (from the analogy of a flickering candle).

There are two practical circuits in which the pure shot effect may set the ultimate noise level. One of these is the circuit in which the grid of an amplifying tube is left "floating" at its equilibrium potential as usually is done in the first stage of amplifiers used for ion counters and other instruments for measuring very small charges.[18, 10] The grid then emits a few electrons and receives positive ions and electrons from the surrounding space. These currents are very small, but are not subject to space charge limitation so far as the grid is concerned. Because the grid impedance is very high, the shot voltage developed by the small grid current may exceed the thermal voltage of the grid impedance. The second circuit is that in which a photo-electric cell works into the amplifier.[19, 20, 21] Vacuum cells generate shot noise of very nearly the theoretical value given by equation (7), while gas-filled cells give even greater noise.

The total noise generated in the output of the vacuum photo-electric cell is the sum of the shot noise and thermal noise across the coupling resistance R, as given by equations (8) and (2). The mean square of the signal voltage, however, is $(\Delta i R)^2/2$ where Δi is the amplitude of the current variation. The ratio of signal to noise is then

$$V_{sg}^2/(V_t^2 + V_s^2) = 1.59 \times 10^{18} \frac{(\Delta i)^2}{F} \frac{R}{iR + 0.0516} \cdot \tag{9}$$

This equation shows the expected fact that for a given value of Δi it is better to keep the direct photo-electric current small (high modulation). It also brings out the curious result that when the direct voltage drop in the coupling resistance is much more than 1/20 volt the noise is largely shot noise and the signal-to-noise ratio is independent of the coupling resistance, while if this voltage is much less than 1/20 volt the thermal noise predominates and the signal-to-noise ratio is proportional to the coupling resistance.

SHOT EFFECT AND FLICKER EFFECT WITH SPACE CHARGE

When, as in an amplifier tube, the current in the tube is limited partly or wholly by space charge rather than by the cathode temperature, then the conditions are changed [13, 14, 16] in two respects. First, while the electrons still are emitted from the cathode at random times, they must arrive at the plate in a more orderly manner. Simple statistical laws no longer apply, the flow of current is smoother and the fluctuations are greatly reduced. Second, the impedance of the tube is no longer infinite, but has a finite value. The equation for the shot effect (equation (7)) now must be modified,[9, 16, 17] by substituting for the current i the quantity $j(\partial i/\partial j)^2$, where j is the total current emitted by the filament and $\partial i/\partial j$ is the rate of change of space current with emission current for the particular conditions used in the observation of the fluctuating voltage. Furthermore, in place of the coupling impedance Z the effective impedance Z_e of this in parallel with the tube resistance r_p must be used. The equation now reads

$$V^2 = 2\epsilon j\left(\frac{\partial i}{\partial j}\right)^2 \int_0^\infty Z_e^2 G^2 df. \tag{10}$$

In the absence of space charge j and i are identical, $\partial i/\partial j$ is unity, and Z_e becomes Z, so that the equation then represents the pure shot effect. With increasing space charge the value of $\partial i/\partial j$ approaches zero and Z_e becomes smaller so that the shot effect becomes very small. Similarly the flicker effect, being connected with the process of emission and not with the subsequent history of the electrons, also is made ineffective by the space charge. In fact, in well designed tubes the fluctuation noise of both shot effect and flicker effect in the space current appears to be reduced to such an extent as to be negligible.

IONS IN THE SPACE CHARGE

The effect of ions in the grid current already has been discussed. Ions also may cause fluctuations in the plate current of the tube.

The space charge which limits the current between cathode and anode consists of electrons in rapid progress toward the anode. A massive ion placed in this region travels much more slowly and contributes to the space charge for a much longer time than does an electron. While its own charge contributes little to the current, one ion may cause the current to change by the amount of hundreds of electrons during its flight through the space charge region, and the action of many ions would be additive.

Probably most of the ions existing in a tube are positive. Some of them are molecules of residual gas that have lost an electron by collision with an electron of the space current. Residual gas has been found to increase the noise of tubes, especially at the higher pressures. Observations at very low pressures are not conclusive, and it is not certain whether in any modern tubes the noise level is determined by the presence of residual gas.[9, 14, 19, 20, 21, 22, 23, 24]

Positive ions may be emitted also by the cathode. These never can attain a high velocity because they remain in a region of low field intensity. They may be trapped for a time in the region of the potential minimum near the cathode before they finally pass to the grid or possibly become neutralized by an electron. In modern tubes with low temperature filaments the effect of these ions is reduced greatly, yet still may account for a large part of the difference between the observed tube noise and the theoretical thermal noise of tubes.[14, 25, 26, 27, 28]

NOISE IN COMMERCIAL TUBES

Noise generated in an amplifier should consist largely of the thermal noise of the input circuit, to which is added the noise produced in the plate circuit of the first tube. It is convenient to consider that the tube noise comes, not from the plate circuit of the tube, but from a fictitious resistance R_G in series with the resistance R_c of the input circuit.[2] The effective thermal noise of the input circuit then is given by the expression

$$V^2 = 4kTF(R_c + R_G) = 1.64 \times 10^{-20} F(R_c + R_G). \qquad (11)$$

The tubes therefore may be rated conveniently in terms of R_G. The transformation to volts or to watts can be accomplished readily by equations (2) or (3). If, with a given tube and circuit, R_G approaches or exceeds R_c in value, the tube is responsible for an appreciable part of the total noise. The choice of another tube in which the ratio of R_c to R_G is more favorable then may be considered.

For the calculation of tube noise several formulas have been proposed, either entirely empirical [2] or with some basis on theory.[9, 24, 29] These formulas generally fail in the prediction of noise in tubes for the reason that the greater part of the noise in practical tubes is caused by things that have not been included in theory and that are still in a state of flux so far as manufacturing is concerned. It is best, therefore, to rely only on actual measurements of the noise in specific types of tubes. With modern tubes, the noise level of a given type of tube can be represented reasonably well by measurements made on a small number of samples.

Published data on noise of tubes are rather meager. The best series of measurements is that of Pearson,[10] which covers four Western Electric tubes at different frequency bands. These tubes are known commercially as types 102*G*, 262*A*, 264*B*, and 259*B*. The General Electric tube type *PJ*-11, designed specially for work at low frequencies, was studied by Metcalf and Dickinson.[24] They also give data, for the low frequency region, on the tubes known commercially as types 222, 240, 201, and 112. Johnson and Neitzert [30] have given data for the *PJ*-11 and the type '38 tube. Certain British tubes were studied by Moullin and Ellis,[29] and of these the type *AC*/2*HL* tube was found to have the lowest noise level. Brintzinger and Viehmann [31] studied a few German tubes. Of these the type *RE*-084 appears to have the lowest noise rating, but the data cannot be reduced to absolute measure.

In many of these studies the tubes were operated at voltages different from those usually employed. For these, the original papers should be consulted. In general for the best triodes R_G has a value of a few thousand ohms, while for screen tubes it has a value of a few tens of thousands. At the lowest voice frequencies the values may be somewhat greater.

OTHER SOURCES OF NOISE

While the more fundamental sources of noise have been discussed, it may be well to add some remarks on a few types of disturbance that often can be eliminated.

Noise From A-C Cathode Heating [32–39]

The indirectly heated cathode may be operated on alternating current when the tube is employed in radio frequency circuits. In audio amplifiers with gains in excess of 50 db, additional precautions must be taken to reduce the effects of the electric and magnetic fields of the heater and of coupling impedance between the heater and the other electrodes. Even under the best conditions, however, the hum level is of the order of 20 db above the tube noise measured with d-c heating.

Noise From Vibration [32, 33, 39, 40]

Mechanical vibration changes the relative positions of the tube elements and hence causes disturbing noise. This is especially objectionable at audio frequency, although a radio frequency carrier may become modulated sufficiently to produce noise.

The remedy, used in the so-called "low microphonic" tube designs, is to stiffen the construction of the tube elements and to apply damping to their vibration, as well as to cushion the tube by a suitable mounting and to shield it from sound waves. The indirectly heated cathode is superior to the filamentary cathode in regard to noise from vibration.

Noise From Poor Insulation [32, 33, 39]

Noise arises from resistance changes at contacts and across thin films of conducting material deposited on insulating supports in the vacuum tube. Leaky capacitors may produce a similar noise.

Noise From Faulty Resistances

Many resistors in which the resistance element is a thin film are sources of noise. If no current flows in them only thermal noise is generated, but when direct current passes through them more noise is produced. The noise voltage is roughly proportional to the direct current. These resistors must be chosen carefully for circuit branches where current flows.

SIGNAL-TO-NOISE RATIO [7, 29, 41, 42]

In so far as noise is concerned, the merit of a transmission system is dependent not only on the amount of noise present, but also on the strength of the signal, so that a determination of the ratio of the signal level to the noise level is necessary. Fortunately, this ratio has a reference value for any given transmission system determined uniquely by the ratio of the signal to thermal noise in the input circuit. The ratio of the signal level to noise level is here the greatest the ratio ever can attain, because noise that originates at subsequent points in the amplifier contributes to the noise level without increasing the signal.

This fact provides a basis for the rating of amplifiers, the thermal noise of the input circuit being used as a comparison signal. For example, the noise output of an amplifying system may be 0.3 mw which falls to 0.2 mw when the input circuit is short-circuited. The thermal noise from the input circuit is then the difference between these two readings, namely, 0.1 mw, and the signal-to-noise ratio of the actual system is 3 times, or 4.8 db worse than its best possible value with a given signal. These data may be expressed in terms of an equivalent input resistance which has the advantage that the amplifying properties of the tube have been taken into account. This leaves for the engineer only the problem of selecting a tube having an input capacity of such a value that the construction of a relatively high impedance input circuit is possible.

So far, the discussion has been based upon the properties of amplifiers only, no mention being made of the effects of modulators, detectors, frequency converters, and other nonlinear devices on the signal-to-noise ratio. A detailed discussion of the noise in such devices is beyond the scope of this paper, but the relations in the most commonly used ones may be indicated and their general properties outlined.

First, consider a system composed of a radio frequency amplifier followed by a detector and a pair of headphones. A certain amount of noise will be heard in the phones if the gain of the amplifier is great enough. This noise is caused by the various components of the radio frequency noise beating together in the detector to form audio frequency components. Next, suppose that an unmodulated carrier is introduced into the amplifier. It will be observed that the audio noise in the phones increases. The increase in audio noise is produced by the radio frequency carrier beating with the radio frequency noise components and this increase is proportional to the strength of the carrier.

If a small percentage of modulation is added to the carrier, the audio signal-to-noise ratio in the phones will be determined by the properties of the amplifier in the same way as though the system were a straight amplifier without any detector. Comparison of the actual system with the ideal may be made by introducing the carrier into one of the amplifier stages subsequent to the input, and then measuring the audio noise with the input circuit in its normal condition and again with the input circuit short-circuited. The ratio of these two energy values gives the ratio of the equivalent input resistance of the actual system to the equivalent input resistance of the noisy amplifier alone. The ratio of the ideal signal-to-noise ratio to the actual one may be found by dividing the difference between the two audio energy readings by the reading taken with the input circuit in its normal condition.

If the percentage of modulation of the carrier is large, the system will be noisier because there will be appreciable audio noise components caused by beats between the side bands and the radio frequency noise components. Again, if the carrier level is not large compared with the noise level in the amplifier, the system will be noisier because the beats between the noise components are appreciable compared with the beats between carrier and the noise.

The same considerations apply to the first detector in a double-detection receiving system. If, as is usual, the beating oscillator voltage is large compared with the noise components, then the frequency band of the noise will be shifted in position in the same manner as the signal, and the signal-to-noise ratio of the system will be unchanged by the frequency conversion.

The signal-to-noise properties of any system are considered satisfactory when the total output noise differs only slightly from that produced by thermal agitation in the input circuit alone, and this difference may be measured by eliminating the input thermal noise (as by the short-circuit method) and noting the change produced in the output noise.

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