LB-964

INVESTIGATIONS OF NOISE IN AUDIO FREQUENCY AMPLIFIERS USING JUNCTION TRANSISTORS

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Approved

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per CWS

INTRODUCTION

The problem of noise in transistor circuits is reviewed, and the results of an extensive investigation of noise from modern junction transistors in audio frequency amplifiers are presented.

Different circuit configurations are examined, and the effects on noise factor of the input termination and operating point are discussed.

Little difference in overall noise factor has been found among the common emitter, base or collector circuits. Generator resistance is not critical although certain values will yield a minimum noise factor. Collector current affects the factor considerably; whereas, collector voltage does not appear to be critical below certain threshold values.

Three distinct sources of noise corresponding to different physical phenomena contributing to total noise are identified. In modern junction transistors shot noise and thermal noise set the ultimate limit of noise in transistor amplifiers, and are frequency independent over the audio spectrum. Semiconductor noise which follows approximately the 1/f law has been found to be just one contributor to total transistor noise.

The concept of equivalent input noise resistance is applied to transistor circuits and a comparison drawn between noise of transistor and vacuum tube amplifiers. Similarities are indicated and it is shown that transistors compare quite favorably with vacuum tubes, even surpassing them in certain cases, where the generator impedance is very low.

REVIEW OF PAST KNOWLEDGE OF NOISE IN TRANSISTOR AMPLIFIERS

A well known and convenient method of expressing the noisiness of a four terminal electrical network is to use the basic concept of noise factor[1] a quantity defined as:

$$NF_{db} = 10 \ log \frac{(S/N)_i}{(S/N)_o} = 10 \ log \frac{N_o}{N_o'} \qquad (1)$$

where S and N are respectively signal and noise powers. The suffixes i and o refer to input and output while the index of N_o' in the denominator indicates that part of N_o which is due to the amplification of the noise from the source.

Most of the work presented in this report will be centered therefore around the presentation, measurements and discussion of the noise factor for various transistor amplifiers. Other types of four terminal networks using transistors in circuits other than amplifiers will not be considered.

Amplifiers using the early point contact type transistors were found to be very poor because of their noisiness and, as such, they could not be used in very low level applications. Noise factors of 50–70 db (measured at 1000 cps) were reported in literature[2] for amplifiers using these early point contact transistors. Clearly any device having such a large noise factor is of little or no use unless the signals to be amplified by it would originate from sources characterized by large value of signal to noise ratio. Since this is hardly the case with most of the practically used low level sources, a widespread impression was created among engineers that transistors were not good for such applications and certainly inferior to vacuum tubes.

With the advent of the first junction transistors it was discovered that much better noise performance could be obtained; noise factors (at 1000 cps) in the range from 10 to 35 db were measured. It was conceivable to hope therefore that even lower noise factors could be obtained as the art progressed so that transistor noise factors comparable with good vacuum tube amplifiers would be available.

When noise at frequencies other than 1000 cps is considered, most previously available information was of such a character that it emphasized the so-called "1/f" law, (the decrease of noise with increasing frequency), reference 2, 3, 7, 8.

POSSIBLE METHODS OF ATTACK

Once the noise factor is taken as the fundamental quantity of interest to electrical engineers, there are clearly two possible ways of attacking the problem. When the physical phenomena active in the noise generation are known it is possible to obtain directly the values of the quantities of equation (1) under different operating conditions and with various circuit configurations. It will then be the purpose of experiments and measurements to check the values of the noise factor obtained theoretically.

Such a procedure is applicable for example, in vacuum tube amplifiers where the noise can be considered as produced by:

a. thermal sources.
b. shot effect in the cathode current.
c. division of fluctuation currents among electrodes.
d. flicker effect at the cathode surface.

When the physical theories for the above noise mechanisms are well established it is possible to proceed directly using the above method. On the other hand when the mechanism of some of the noise generators is totally or partially unknown it is advisable to proceed with direct experimental techniques by measuring the noise factor of amplifiers operated under different conditions; such an approach while yielding direct information on the usefulness of the device as an amplifier also offers the possibility of some later understanding of the physics of noise generation.

Transistor amplifiers have been investigated by the latter type of approach since no generally acceptable model for the noise generating mechanisms active in the transistor itself was available at the time this investigation was started. Theories of noise in semiconductor devices have been advanced[4] but they appeared insufficient to predict the noise behavior of a transistor amplifier. The "1/f" law itself was questioned with respect to its general application and it was decided to carefully investigate the limits of its validity. It will be shown later that in modern, quiet, junction transistors, the "1/f" law must be substantially corrected. The correction was the conclusive element leading to a formulation of a novel transistor noise equivalent circuit.

THE FORMULATION OF THE NOISE PROBLEM FROM THE FOUR TERMINAL NETWORK POINT OF VIEW

It has been shown[5] that in order to describe a noisy four terminal network of the active type, six parameters are required. Four of them being the usual Z, Y or H parameters[6] while the additional two represent two fictitious noise generators such as open circuit input and output voltage generators, or an open circuit voltage generator and another short circuit current generator.

To completely specify the above six parameters twelve real quantities are needed, since the four Z, Y or H parameters are complex and the two noise generators must be specified by their two real power spectra and by their complex cross spectrum. Sometimes the latter part of the above statement is expressed in the form that the statistical correlation between the two noise generators must be known.[7]

When, for example, voltage generators are used for the noise sources, the noisy four terminal network can be replaced by the cascade arrangement of three four terminal networks as in Figure 1.

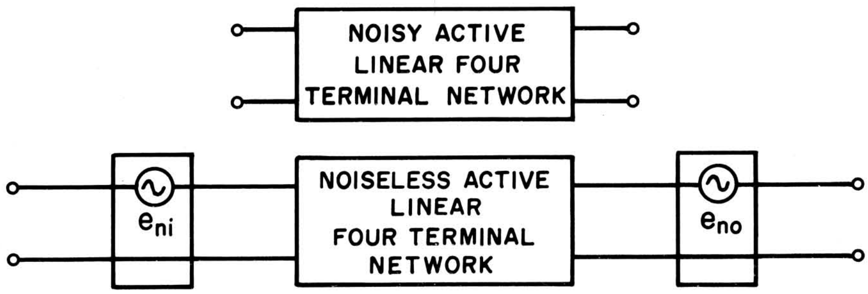


FIGURE 1. GENERAL REPRESENTATION OF A NOISY FOUR TERMINAL NETWORK.

When the network is connected to a generator on one side and to a load on the other, the noise factor of the amplifier resulting from the combination can be found.

In the general case the spot (single frequency) noise factor F_o is given in terms of the Z parameters by:

$$F_o = 1 + \frac{1}{4KT\,R_g}\left[N_i + N_o\left|\frac{Z_{11} + Z_g}{Z_{21}}\right|^2 - 2\,R_e\left(N_{io}\,\frac{Z_{11} + Z_g}{Z_{21}}\right)\right] \quad (2)$$

or in terms of the Y parameters:

$$F_o = 1 + \frac{1}{4KT\,G_g}\left[N_i' + N_o'\left|\frac{Y_{11} + Y_G}{Y_{21}}\right|^2 - 2\,R_e\left(N_{io}'\,\frac{Y_{11} + Y_G}{Y_{21}}\right)\right] \quad (3)$$

or in terms of the H parameters:

$$F_o = 1 + \frac{1}{4KT\,R_g}\left[N_i + N_o'\left|\frac{H_{11} + Z_g}{H_{21}}\right|^2 + 2\,R_e\left(N_{io}''\,\frac{H_{11} + Z_g}{H_{21}}\right)\right] \quad (4)$$

where: R_g, G_g = generator resistance, conductance (respectively)

N_i = power spectrum of e_{ni}
N_o = power spectrum of e_{no}
N_{io} = cross power spectrum of e_{ni} and e_{no}

N_i' = power spectrum of i_{ni}
N_o' = power spectrum of i_{no}
N_{io}' = cross power spectrum of i_{ni} and i_{no}

N_i = power spectrum of e_{ni}
N_o' = power spectrum of i_{no}
N_{io}'' = cross power spectrum of e_{ni} and i_{no}

The influence of the third term which is descriptive of correlation between the noise generators has been the object of previous studies (reference 2 and 7). Although it seems to have a certain importance in the case of very noisy transistors it appears that in low noise units its importance decreases because the noise levels are close enough to values which can be ascribed, as it will be shown later, to uncorrelated thermal and shot noise sources.

By eliminating the third term the noise factor can be written in the simplified form:

$$F_o = 1 + \frac{1}{4KT\,R_g}\left[\overline{e_{ni}^2} + \overline{e_{no}^2}\left|\frac{Z_{11} + Z_g}{Z_{21}}\right|^2\right] \tag{5}$$

and with a further simplification whereby all Z's reduce to R's:

$$F_o = 1 + \frac{1}{4KT\,R_g}\left[\overline{e_{ni}^2} + \overline{e_{no}^2}\left(\frac{R_{11} + R_g}{R_{21}}\right)^2\right] \tag{6}$$

with:

$\overline{e_{ni}^2}$ = open circuit input generator mean squared volts

$\overline{e_{no}^2}$ = open circuit output generator mean squared volts

or:

$$F_o = 1 + \frac{1}{4KT\,G_g}\left[\overline{i_{ni}^2} + \overline{i_{no}^2}\left(\frac{G_{11} + G_g}{G_{21}}\right)^2\right] \tag{7}$$

for the current generator form,

or:

$$F_o = 1 + \frac{1}{4KT\,R_g}\left[\overline{e_{ni}^2} + \overline{i_{no}^2}\left(\frac{H_{11} + R_g}{H_{21}}\right)^2\right] \tag{8}$$

for the hybrid case where H parameters are used.

Expressions (6), (7), and (8), should be considered equivalent, and the use of them is a matter of convenience related to direct noise measurements of noise voltages or currents.

Developing equation (6) for the three basic transistor amplifier configurations common-base, common-emitter and common-collector it is found:

Common-Base

$$F_o = 1 + \frac{1}{4KT\,R_g}\left[\overline{e_{ne}^2} + \overline{e_{nc}^2}\left(\frac{r_e + r_b + R_g}{r_m + r_b}\right)^2\right] \tag{9}$$

Common-Emitter

$$F_o = 1 + \frac{1}{4KT\,R_g}\left[\overline{e_{ne}^2}\left(\frac{r_m + r_b + R_g}{r_m - r_e}\right)^2 + \overline{e_{nc}^2}\left(\frac{r_e + r_b + R_g}{r_m - r_e}\right)^2\right] \tag{10}$$

Common-Collector

$$F_o = 1 + \frac{1}{4KT\,R_g}\left[\overline{e_{ne}^2}\left(\frac{r_b + r_c + R_g}{r_c}\right)^2 + e_{nc}^2\left(\frac{r_b + R_g}{r_c}\right)^2\right] \tag{11}$$

The above expressions correspond respectively to the three arrangements of the noise generators of Figure 2.

If the short circuit current amplification factor:

$$\alpha = \frac{r_m + r_b}{r_e + r_b} \cong \frac{r_m}{r_c}$$

is introduced in equations (9), (10) and (11) one finds further equivalent expressions for the noise factor:

Common-Base

$$F_o = 1 + \frac{1}{4KT\,R_g}\left[\overline{e_{ne}^2} + \overline{e_{nc}^2}\left(\frac{r_e + r_b + R_g}{\alpha r_c + r_b}\right)^2\right] \tag{12}$$

Common-Emitter

$$F_o = 1 + \frac{1}{4KT\,R_g}\left[\overline{e_{ne}^2}\left(\frac{\alpha r_c + r_b + R_g}{\alpha r_c - r_e}\right)^2 + \overline{e_{nc}^2}\left(\frac{r_e + r_b + R_g}{\alpha r_c - r_e}\right)^2\right] \tag{13}$$

Common-Collector

$$F_o = 1 + \frac{1}{4KT\,R_g}\left[\overline{e_{ne}^2}\left(\frac{r_c + r_b + R_g}{r_c}\right)^2 + \overline{e_{nc}^2}\left(\frac{r_b + R_g}{r_c}\right)^2\right] \tag{14}$$

Inspection of equations (9), (10) and (11) or (12), (13) and (14), taking into account that it is in most cases permissible to consider

$$r_e \ll r_c \cong r_m,$$
$$r_b \ll r_c \cong r_m,$$
$$R_g \ll r_c \cong r_m$$

shows that very little difference should be found in the value of noise factor for the three different amplifier configurations, since the multiplier of $\overline{e_{ne}^2}$ is very close to unity and the multiplier of $\overline{e_{nc}^2}$ is approximately equal for all three cases. These facts have been confirmed through experiments.

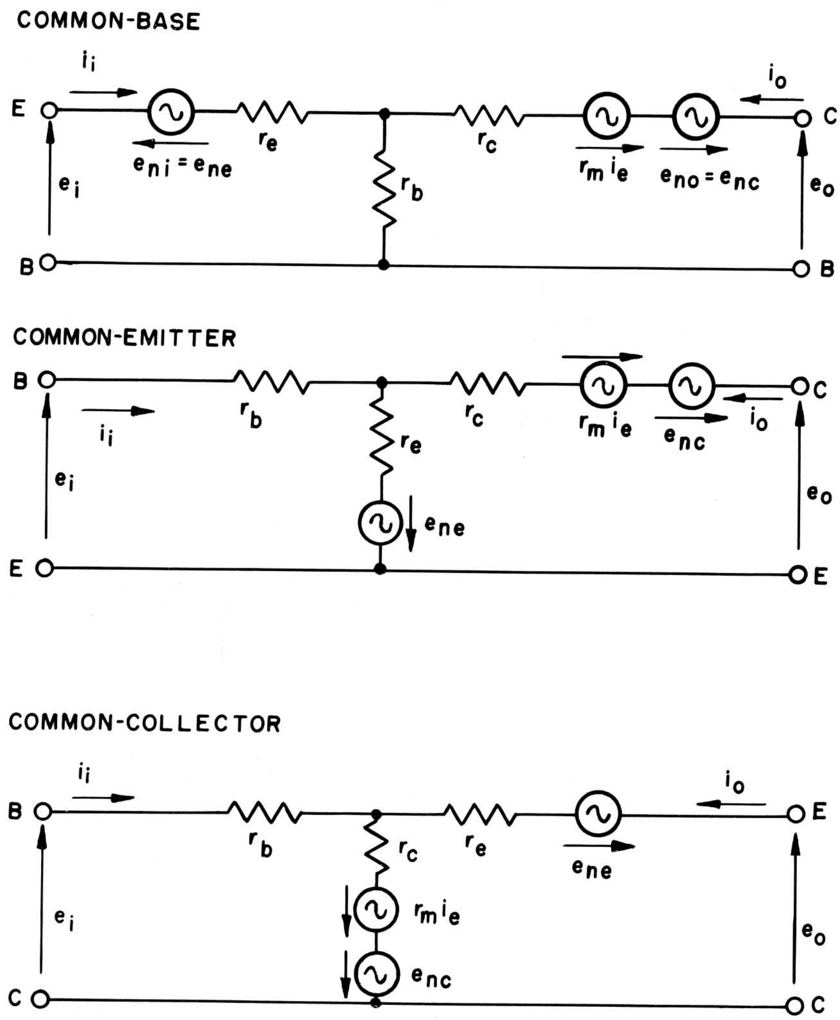


FIGURE 2. BASIC TRANSISTOR EQUIVALENT CIRCUITS WITH NOISE GENERATORS.

CONSIDERATIONS ON e_{ni} AND e_{no}, THEIR MEASUREMENT AND NATURE

In equations (9) to (14) the noise mean squared voltages must be defined over a one cycle bandwidth at any point of the frequency spectrum for which it is desired to obtain the value of F_o. However F_o cannot be determined from these equations unless e_{ne} and e_{nc} are known. Direct measurements have been reported (reference (2 and 6)) and some indicative values at 1000 cps are available for point contact transistors ($e_{ne} = 10^{-6}$ volts, $e_{no} = 10^{-4}$ volts). Both noise voltages are functions of the operating conditions, particularly of the d-c voltages and currents in the input and output junctions. Precise data[8] was not available at the beginning of this investigation on junction transistors.

The transistor has to be made effectively operative if the noise voltages (or currents) are to be measured; taking into account their very definition in terms of open or short circuit conditions at the generator and/or load end, it is seen that direct determinations are not easy to obtain in general, not only because of the very small noise voltages or currents to be measured but also because of the required impedance levels which are often in contrast with the requirements of the bias circuits.

A different approach to determine the noise voltages is possible. Since the generator impedance enters in the expressions of noise factor the functions

$$F_o = f\,(R_g)$$

are obtained experimentally for any of the three different configurations and for a given transistor. Taking then two values of R_g so as to yield two values of F_o, two equations in two unknowns, e_{ni} and e_{no}, can be obtained.

In the case of the common-base connection, equation (9) can thus be written twice:

$$F_{o1} = 1 + a_1 [\overline{e_{ne}^2} + \overline{e_{nc}^2}\,(b_1)^2]$$

$$F_{o2} = 1 + a_2 [\overline{e_{ne}^2} + \overline{e_{nc}^2}\,(b_2)^2] \qquad (15)$$

where:

$$a = \frac{1}{4KT\,R_g}$$

$$b = \frac{r_e + r_b + R_g}{r_m + r_b}$$

Solving equations (15) it is found:

$$\overline{e_{ne}^2} = \frac{a_1 b_1^2 (F_{o1} - 1) - a_2 b_2^2 (F_{o2} - 1)}{a_1 a_2 (b_1^2 - b_2^2)} \qquad (16)$$

$$\overline{e_{nc}^2} = \frac{a_2 (F_{o1} - 1) - a_1 (F_{o2} - 1)}{a_1 a_2 (b_1^2 - b_2^2)} \qquad (17)$$

Similar relationships can be obtained for the other two connections but would bring no new information on e_{ne} and e_{nc}. The results of measurements producing values of e_{ne} and e_{nc} are given further on in this report.

In any problem of this kind the knowledge of the optimum source resistance R_g yielding minimum noise factor is of importance. Thus setting

$$\frac{\partial F_o}{\partial R_g} = 0$$

and solving for R_g it is found in the general case that:

$$R_{g\ \mathrm{OPTIMUM}} = \sqrt{r_{21}\left(\frac{e_{n1}}{e_{n2}}\right)^2 + r_{i1}^2} \tag{18}$$

For the three different configurations it is found:

Common-Base

$$R_{g\ \mathrm{OPTIMUM}} = \sqrt{\left(\frac{e_{ne}}{e_{nc}}\right)^2 (r_b + r_m)^2 + (r_e + r_b)^2} \tag{19}$$

Common-Emitter

$$R_{g\ \mathrm{OPTIMUM}} = \sqrt{\frac{r_b^2 + r_m^2 (e_{ne}/e_{nc})^2}{1 + (e_{ne}/E_{nc})^2}} \tag{20}$$

Common-Collector

$$R_{g\ \mathrm{OPTIMUM}} = \sqrt{\frac{\left(\frac{e_{ne}}{e_{nc}}\right)^2 r_c^2 + r_b^2}{1 + \left(\frac{e_{ne}}{e_{nc}}\right)^2}} \tag{21}$$

The above values check with the experimental determinations.

It is well to remember at this time that although e_{ni} and e_{no}, or as a matter of fact e_{ne} and e_{nc}, can be determined in this way still nothing is known of the physical phenomena which are their cause.

Previously available information concerning e_{ne} and e_{nc} indicated that these noise voltages are frequency dependent, the type of dependence being described by the already mentioned inverse frequency law. Since it has already been mentioned that it was necessary to reconsider the "1/f" law the dependence of noise sources and consequently of noise factor on frequency is of extreme importance. Notice that equation (1) in yielding noise factor leads to different values of this quantity which are usually indicated as:

a. single frequency or spot noise factor
b. integrated noise factor.

which are respectively:

$$NF(f) = 10 \ log \frac{N_o(f)}{N'_o(f)} \tag{23}$$

$$NF_{INT} = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} NF(f)df \tag{24}$$

where $N_o(f)$ and $N'_o(f)$ are now the output noise power densities (watts/cycle) of the thermal and total noise.

Since $N'_o(f)$ is frequency dependent only through the amplitude squared function of the device, while $N_o(f)$ is a function of the location and mechanism of the various noise generators a difference may result between spot and integrated noise factors.

DESCRIPTION OF NOISE FACTOR MEASUREMENTS – METHODS, TECHNIQUES AND PRECAUTIONS

Several methods and techniques are available for measuring the noise factor of an amplifier. However, these might be classified into two main categories:

a. methods employing a noise source such as a noise diode
b. methods using a sinusoidal signal generator.

The noise diode method of measuring noise factor is quite fundamental; it permits simplification in the procedure and, in general, a greater accuracy than other methods. Techniques employing a sinusoidal signal generator become easily subject to noticeable error in the measurement of the extremely small power levels employed, especially at higher frequencies; furthermore a separate measurement of amplifier bandwidth is required. On the other hand the use of a temperature-limited diode as a noise generator makes possible the cancellation of the bandwidths involved since the spectrum of the diode noise is flat, hence this method requires no measurement or knowledge of bandwidth and gain.

With the noise source turned off, the noise power output of the amplifier is measured. The noise source is then turned on and the diode direct plate current is adjusted to a value where the amplifier noise power output just doubles. The expression[1C] for the noise factor of the amplifier then becomes:

$$F = 20 \, I_d \, R_a$$

where:

I_d = diode plate current (amperes)
R_a = internal resistance of source (ohms)

A block diagram of the noise diode setup used is shown in Figure 3. In order to reduce stray and hum fields which would introduce errors, the amplifier is shielded and the noise diode filament and plate supplies are obtained from batteries.

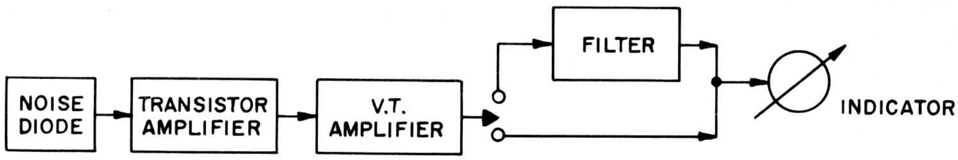


FIGURE 3. BLOCK DIAGRAM OF NOISE FACTOR MEASUREMENT SETUP WITH RANDOM NOISE GENERATOR.

The signal from the transistor amplifier is fed directly to a low noise tube amplifier using a 1620 tube in the input stage; the noise power output may be read at its output or may be channeled to a General Radio Wave Analyzer, Model 736-A.

Measurements taken with the wave analyzer yield essentially spot noise factor values since the analyzer has a constant noise bandwidth of 5.3 CPS over the audio band. When the analyzer is not employed, and since the noise bandwidth of the 1620 set is 12 Kc, noise factor values integrated throughout theaudio band are obtained. Integrated noise factor measurements are usually desirable since they describe more accurately the device under investigation, or several spot noise factor measurements at different frequencies should be taken.

For the experimental results to be found in the next section, it should be noted that the greater percentage of noise measurements were taken using the noise diode set-up. The narrow band results obtained were also compared with various signal generator methods of measurement and were found to be in close agreement. One of the most reliable of these methods and which will provide excellent agreement with the noise diode will be described.

In an amplifier being fed from a source having an internal resistance R_g as shown in Figure 4, the thermal noise voltage from R_g is:

$$e_{THERMAL} = \sqrt{4KTBR_g}$$

When this voltage has been calculated it is only necessary to inject at the desired frequency a substantially high level signal E,(20 db higher than the computer noise voltage). (In the case of

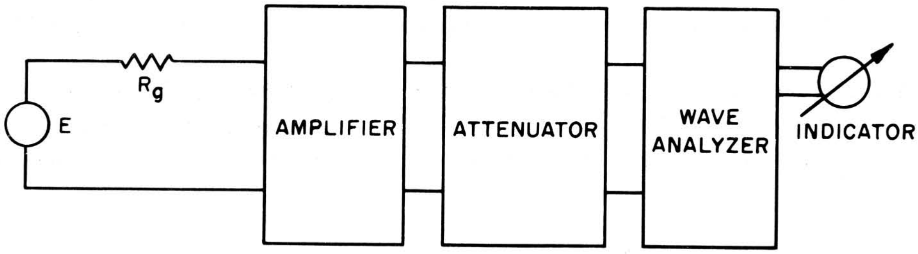


FIGURE 4. BLOCK DIAGRAM OF NOISE FACTOR MEASUREMENT SET UP WITH SINGLE FREQUENCY SIGNAL GENERATOR.

transistors with noise factors greater than 20 db, the voltage, E, should be larger so as to produce a signal output from the amplifier which is at least 10 db greater than the noise output). The output voltage is noted; the signal source is now removed and 20 db gain is added to the system. The attenuation required to bring the output voltage to its original level is a measure of the noise factor of the amplifier, since noise factor is defined as total noise output divided by that portion due to the thermal noise of the source. Using this technique, no direct measurement of the amplifier gain is required.

When taking noise factor measurements, care must be exercised not to introduce extraneous noise voltages. All resistors in the the transistor amplifier are wire wound including the load resistor since, in the common-collector, and sometimes in the common-base connections, the amplifier gain may be low enough that a carbon load resistor could introduce considerable error in the measurements (especially when the effect of increased noise by the direct current flowing through the resistor is taken into account).

EXPERIMENTAL RESULTS

Noise factor measurements of PNP and NPN junction transistors were conducted. Almost all the different types of transistors manufactured were investigated although the RCA type 2N34 transistor was given preference due to the importance of this type for low level audio work.

It was recognized at an early stage of the experimental program that the "1/f" law is not always verified in junction transistors throughout the whole audio range; as a consequence it was decided to adopt as a possible measure of the noise quality of a transistor the integrated (over the "audio" band) value of its noise factor rather than the spot or single frequency noise factor usually given at 1 Kc.

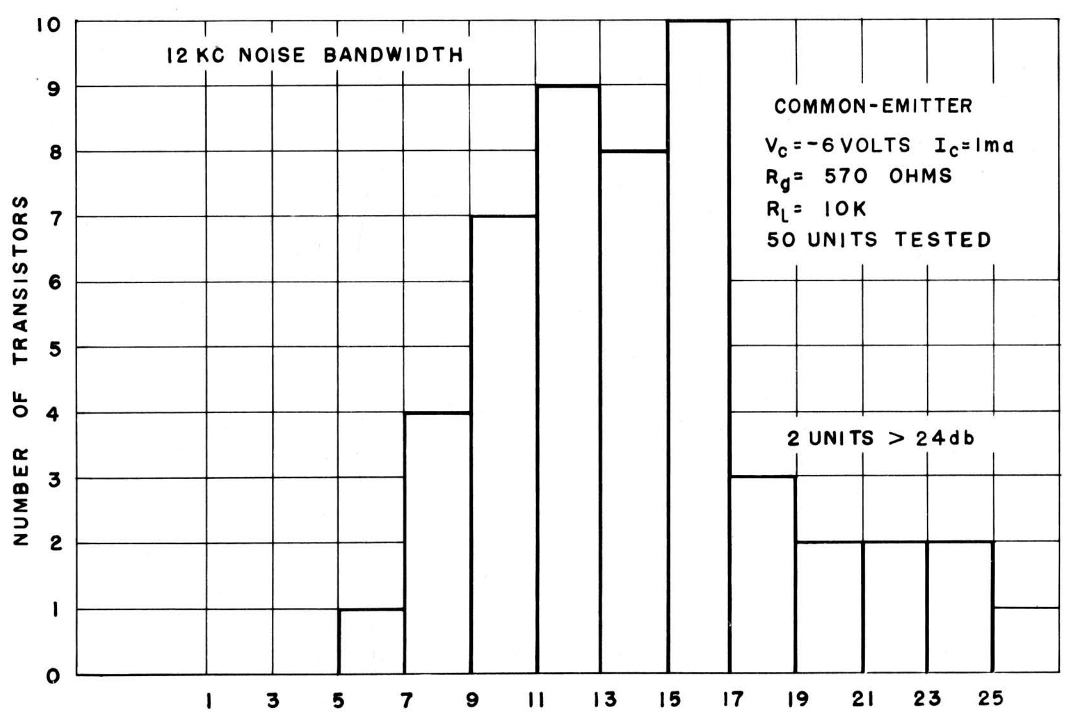


FIGURE 5. INTEGRATED NOISE FACTOR DISTRIBUTION.
RCA-2N34

In assigning the limits to the above mentioned band of frequencies it was kept in mind that:

a. the lower limit should be set considerably below the lowest audible frequency because it is usually in this region that the "1/f" law holds as the result of the predominant "semiconductor noise". The adopted value was 20 cps.

b. the higher limit should be set around the highest audible frequency, the exact value being immaterial. The 12 Kc noise bandwidth of the tube noise set was thereby acceptable and use of the set was made for experimental convenience.

The 2N34 transistors tested were generally found to have relatively low noise factors. From a random sample of 50 new units tested the average integrated noise factor was found to be about 13 or 14 db. The measurements of integrated noise factor gave the results in Figure 5 for the specified conditions.

Measurements of single frequency noise factors are given in Figure 6 for the specified conditions. The most important conclusions on the basis of this experimental evidence is that the noise behavior of transistors is not unique; there are not only quiet and noisy transistors, but each type exhibits a different behavior as is clearly indicated in the figure.

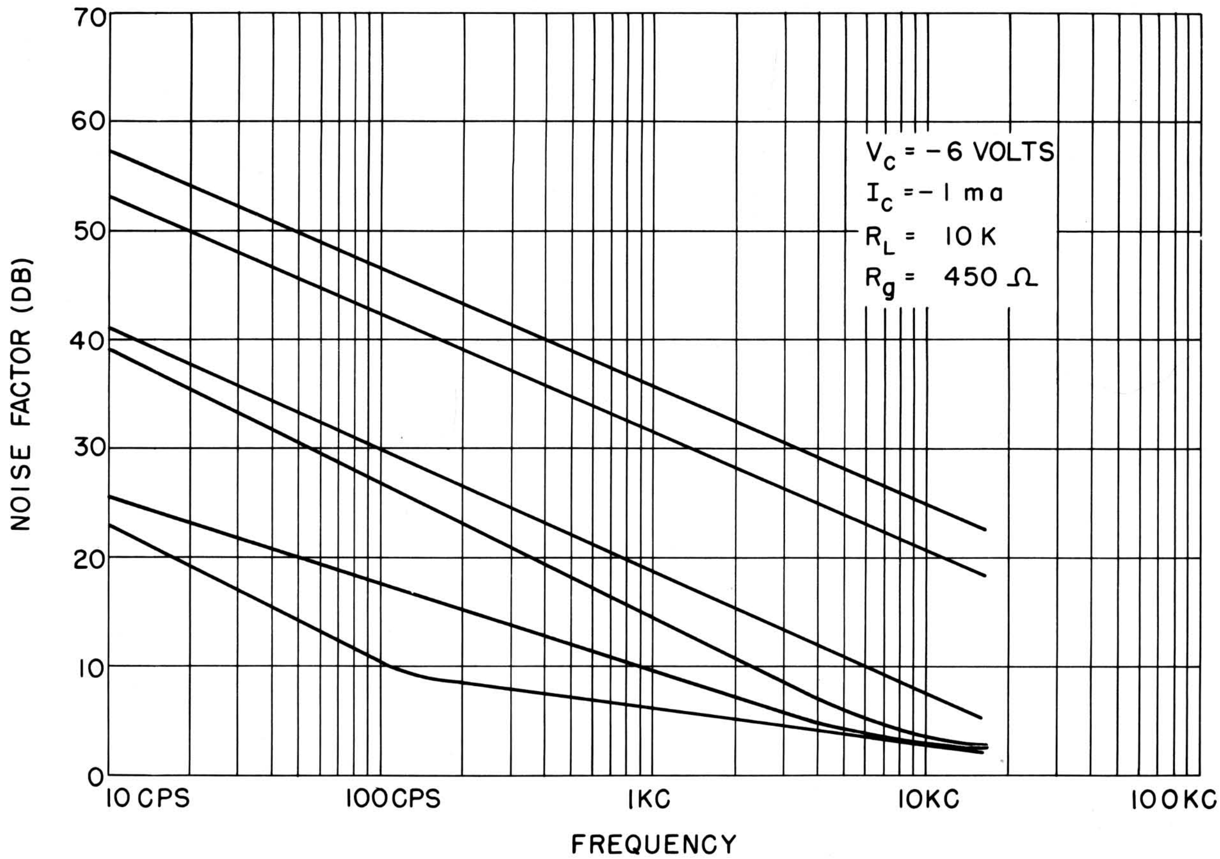


FIGURE 6. NOISE FACTOR vs. FREQUENCY (RCA 2N34; COMMON EMITTER)

The change in the spot noise factor value over a decade frequency interval ranges from 12 db to 3 db depending on a given transistor and on the position in the spectrum of the frequency interval.

In general the experimental evidence indicates that noisy units approximately follow the "1/f" law throughout the whole audio frequency range and above, while quiet units exhibit different slopes in different regions, eventually exhibiting a somewhat flat spectrum.

Theoretically, whether the transistor is connected common-emitter, common-base, or common-collector, its noise factor should be approximately the same. This has been substantiated experimentally for several transistors as shown in Figure 7. It may be noted that measurements for the various connections are within 2 db of each other.

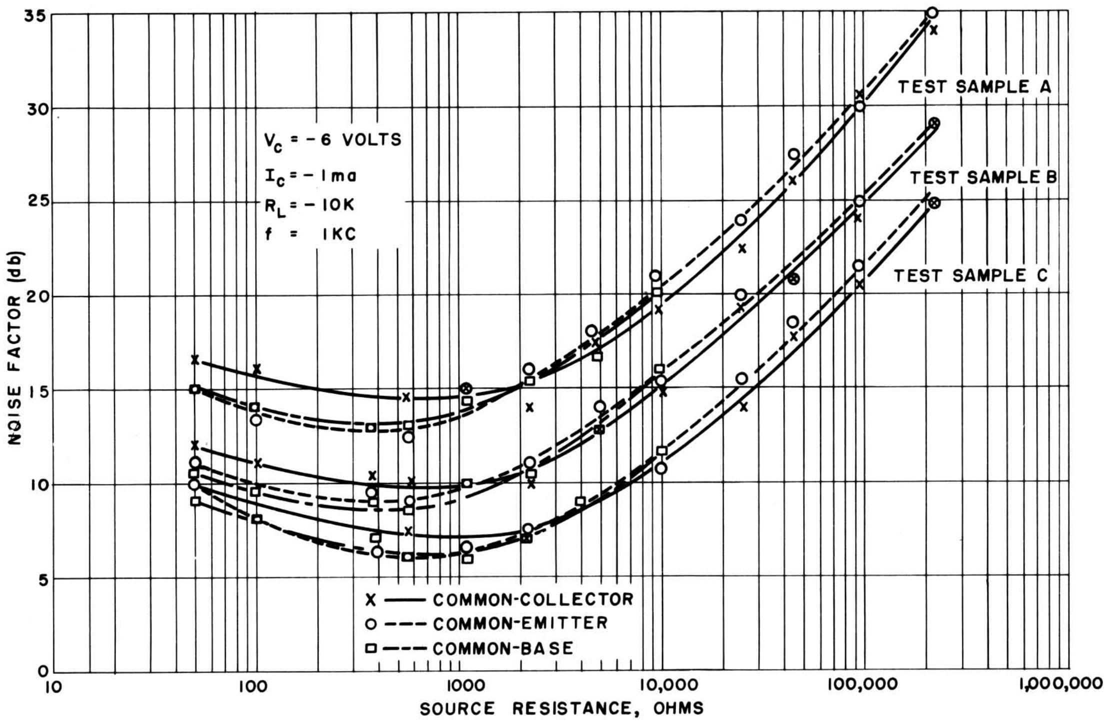


FIGURE 7. NOISE FACTOR VS. SOURCE RESISTANCE RCA 2N34

From the designer's point of view, it is of interest to know the value of source impedance which will yield optimum noise factors. Figure 7 shows a broad minimum value of noise factor, from which it may be concluded that source impedance is not a critical value; however, for best results, the device should be operated from a source having an impedance in the range between 400 and 1000 ohms. The results shown are spot noise factor measurements taken at a frequency of 1 Kc. If integrated noise factor measurements are made, Figure 8 shows that the results are quite similar, with the integrated noise being lower than the spot noise measurements; the exact value depends on the transistor spot noise factor versus frequency characteristic.

Mention has been made in the literature about the dependence of noise in transistors upon the operating biases; usually the effects on noise of collector current, I_C, and voltage V_C, are emphasized. A study of such effects is useful in separating the semiconductor and shot noise components provided that an investigation of the effects of I_C, or V_C, on noise factor is carried out at several frequencies.

Figure 9 refers to the typical behavior of an RCA 2N34 transistor operated at a constant collector voltage with different values of collector current; it is significant to notice the change in level and shape of the noise factor versus frequency curves.

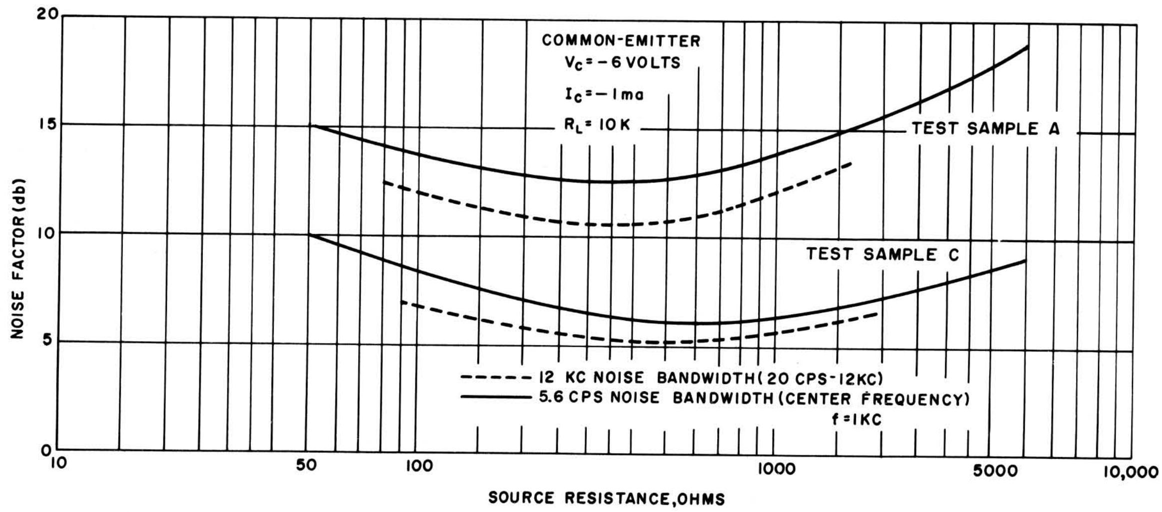


FIGURE 8. NOISE FACTOR VS. SOURCE RESISTANCE
RCA 2N34

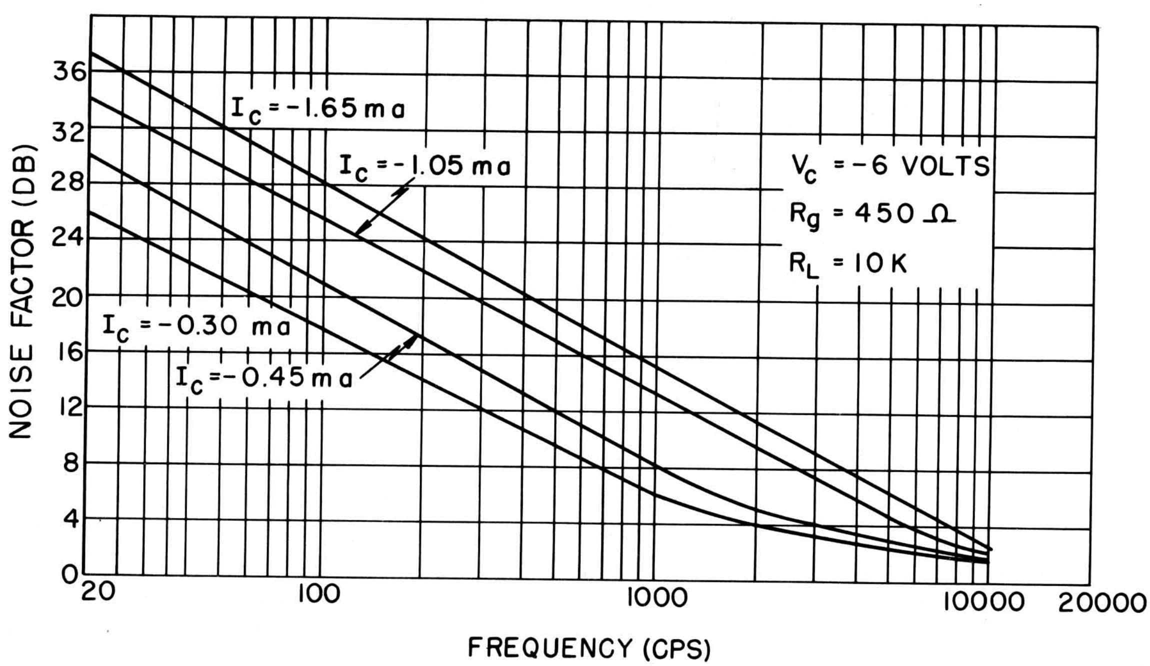


FIGURE 9. NOISE FACTOR vs. FREQUENCY
(COLLECTOR CURRENT AS A PARAMETER)
(RCA 2N34; COMMON-EMITTER)

Figure 10 gives noise factor at 1 Kc versus collector current I_C, with collector voltage V_C, as a parameter, while Figure 11 shows noise factor at 1 Kc versus collector voltage with collector current taken as a parameter.

The three previous figures refer to amplifiers in the common-emitter connection; further tests have constantly revealed no appreciable difference for the two other connections as far as depen-

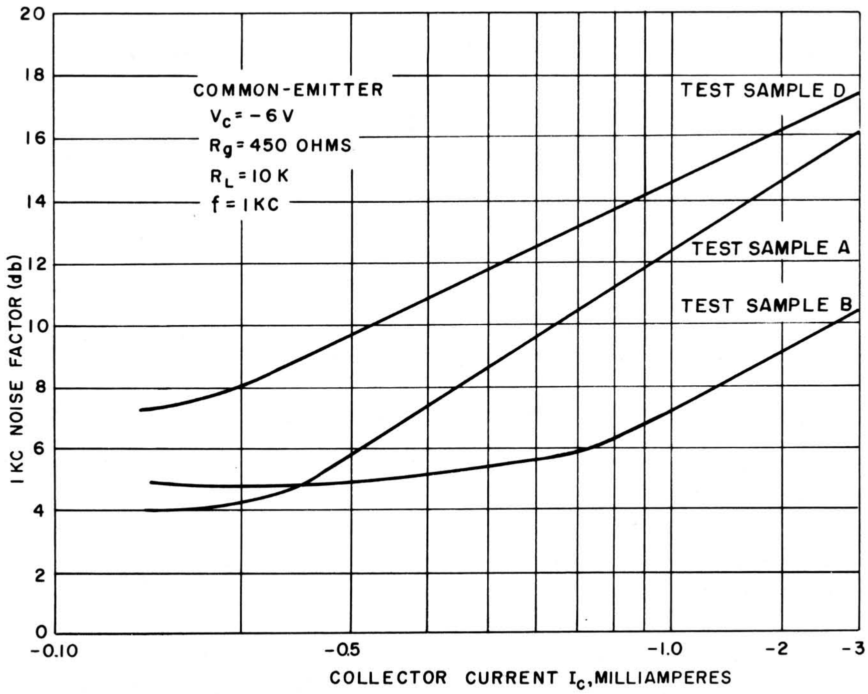


FIGURE 10. NOISE FACTOR VS OPERATING POINT (COLLECTOR CURRENT)

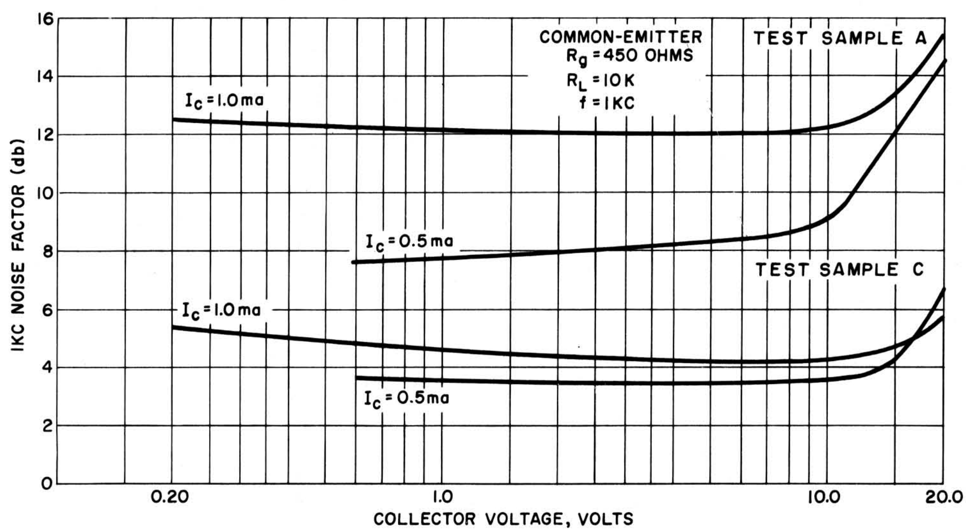


FIGURE 11. NOISE FACTOR VS OPERATING POINT (COLLECTOR VOLTAGE) RCA-2N34

dence upon d-c biases is concerned. The conclusions to be drawn from the above experimental evidence are:

a. Modern, well constructed transistors are much quieter than previously available units. Selected low noise transistors should have a noise factor below 12 to 15 db.
b. Remarkably quiet units were found with minimum values of noise factor around 4 db.
c. All three connections, common-base, emitter or collector are capable of resulting in

essentially identical values of noise factor. The lower power gain of the common collector connections advises against its use whenever second stage noise would be objectionable.

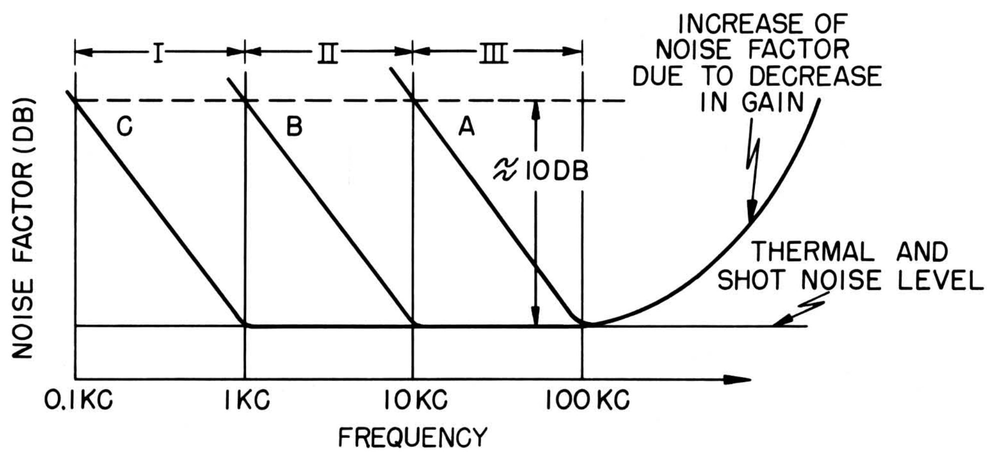
d. Source resistance has an influence on minimum noise factor. Optimum values are not critical however and typical values have been reported for the three different connections.
e. The "1/f" law is observed only through part of the spectrum and the frequency dependence of noise factor or the applied d-c bias is indicative of the superposition of various noise sources having different spectral distributions.
f. No appreciable reduction of noise is obtained below $V_C = 10$ volts. Above this range however the noise increases sharply with increasing collector voltage.
g. Reduction of collector current results generally in more quiet operation.

SEPARATION OF NOISE SOURCES, PHYSICAL EQUIVALENT CIRCUITS FOR NOISY TRANSISTORS.

Experimental evidence has indicated that the noise behavior of a transistor amplifier expressed in terms of noise factor can be described as follows:

a. at very low frequencies the noise decreases with increasing frequency (region I).
b. in an intermediate range of frequencies the noise remains relatively constant (region II).
c. at higher frequencies the noise increases with frequency (region III).

The definition of these three regions is a function of many variables and as indicated by the idealized curves of Figure 12 their interval of existence is different for various transistors operated under different conditions. The general trend of the curves of Figure 12 has been inferred not only from the measurement at audio frequencies but also correlates well with radio frequency measurements in the range from 500 Kc. to 8 Mc.



A. OLD TRANSISTOR WITH LARGE AMOUNT OF SEMICONDUCTOR NOISE.
B. IMPROVED TRANSISTOR WITH MODERATE AMOUNT OF SEMI-CONDUCTOR NOISE.
C. MODERN TRANSISTOR WITH VERY SMALL AMOUNT OF SEMI-CONDUCTOR NOISE.

FIGURE 12. GENERALIZED BEHAVIOR OF TRANSISTOR NOISE

It must be added that the noise levels effectively measured for region II are not equal but depend on the particular transistor and circuit used.

At present one can only hypothesize as to the exact nature of transistor noise generating mechanisms. Based upon available information in the literature and upon the measurements considered the following analysis seems plausible with the possible active noise sources being those due to:

a. thermal agitation.
b. shot effect in the current carriers.
c. semiconductor (or excess) noise.
d. leakage.

All these sources contribute to form the e_{ne} and/or e_{nc} noise voltages at any given frequency, therefore, they must be investigated separately to correctly interpret the noise from transistors.

Leakage noise, characterized by abnormally large bursts (pops) has been observed in the course of this work, especially on poor and unreliable units. It was decided however, to reject units with excessive leakage since this type of noise is due to manufacturing techniques and is not necessarily inherent in the device.

Semiconductor noise is that component of noise (considered in the past as the only transistor noise) which is observed in non metallic resistors, carbon microphones, and semiconductor devices when a circuit current is made to flow through them; the mean square noise voltage from a semiconductor has been hypothesized[9] to be:

$$\overline{de^2} = kV^{\alpha}R^{\beta}f^{-\gamma} \cdot df \tag{25}$$

where:

k = a factor dependent on the material used.
V = applied d-c voltage.
R = d-c resistance.
f = frequency.
α = a factor from 1.2 to 1.8
β = a factor from 1.2 to 1.8
γ = a factor from 0.9 to 1.2

From equation (25) it may be inferred that noise is dependent on d-c voltage and d-c resistance; therefore noise will be many times higher in a reverse than in a forward biased junction.

If the exponent γ is given the value of unity and all other conditions are left unchanged the noise mean square voltage over a frequency interval from f_1 to f_2 will be:

$$\overline{e_{sc}^2} = C\int_{f_1}^{f_2} \frac{df}{f} = \frac{C}{f_2 - f_1}\, ln \frac{f_2}{f_1} \tag{26}$$

where C is a constant incorporating all the above factors exclusive of frequency.

In a transistor considered as two adjacent semiconductor junctions displaying a mutual interaction there are two semiconductor noise sources; one in the emitter to base and one in the collector to base junctions. Mention will be made later of their relative importance.

Shot noise from a rectifying junction can be expressed as:

$$di^2_{SHOT} = 2eIdf \qquad (27)$$

where:

e = electron charge
I = d-c current through the junction

The above current source is in parallel with the junction dynamic resistance r_d so that the mean square voltage across it is:

$$\overline{de^2_{SHOT}} = \overline{di^2} \cdot r_d^2 \qquad (28)$$

As in the case of semiconductor noise, two shot-noise sources have to be considered in a transistor; one in the emitter to base junction and another in the collector to base junction. Since the output (collector) direct current is the sum of the thermal equilibrium current I_{co} and the current injected from the input circuit, care must be exercised to use the correct values of the d-c components of the current and of the dynamic resistances in equations (27) and (28).

The extension to transistors of equation (27) was recently discussed[10] in the literature in an attempt to investigate the lower noise limits of transistors. Substantial agreement has been found between the results of the above reference and the work reported here, which was carried out independently.

Finally thermal noise from resistive components in the transistor not otherwise considered must be taken into account yielding voltages of the form:

$$\overline{de^2_{TH}} = 4KTRdf \qquad (29)$$

In a transistor there are three resistances of the above type associated with each of the three terminals: base, emitter and collector. The intrinsic base resistance (sometimes called spread base resistor or $r_{bb'}$) is the only term of importance however, and the other two (lead emitter and collector resistances) can be neglected.

It can therefore be concluded that the effective noise sources in a transistor are:

a. one thermal source in the base resistance.
b. two shot noise sources in the input and output junctions.
c. two semiconductor noise sources in the input and output junctions.

Notice that while the sources under (a) and (b) can be considered as frequency independent (at least within the audio frequency range) and those of (c) frequency dependent, some of the above contributions may result in quantities small enough to make it permissible to neglect them. Such is the case, as indicated by experimental evidence, with semiconductor noise which is originated for its greater part in the collector junction. With reference to Figure 12, while region I is ascribed to semiconductor noise, and regions II and III to shot and thermal noise, the increase of noise factor of the latter is explained as due to the effect of the decrease in the power gain of the amplifier (and possible intervention of additional noise sources) at high frequencies and the presence of shot noise from the output junction. The physical equivalent circuits for noisy transistors in the three basic circuit configurations can therefore be drawn as in Figure 13.

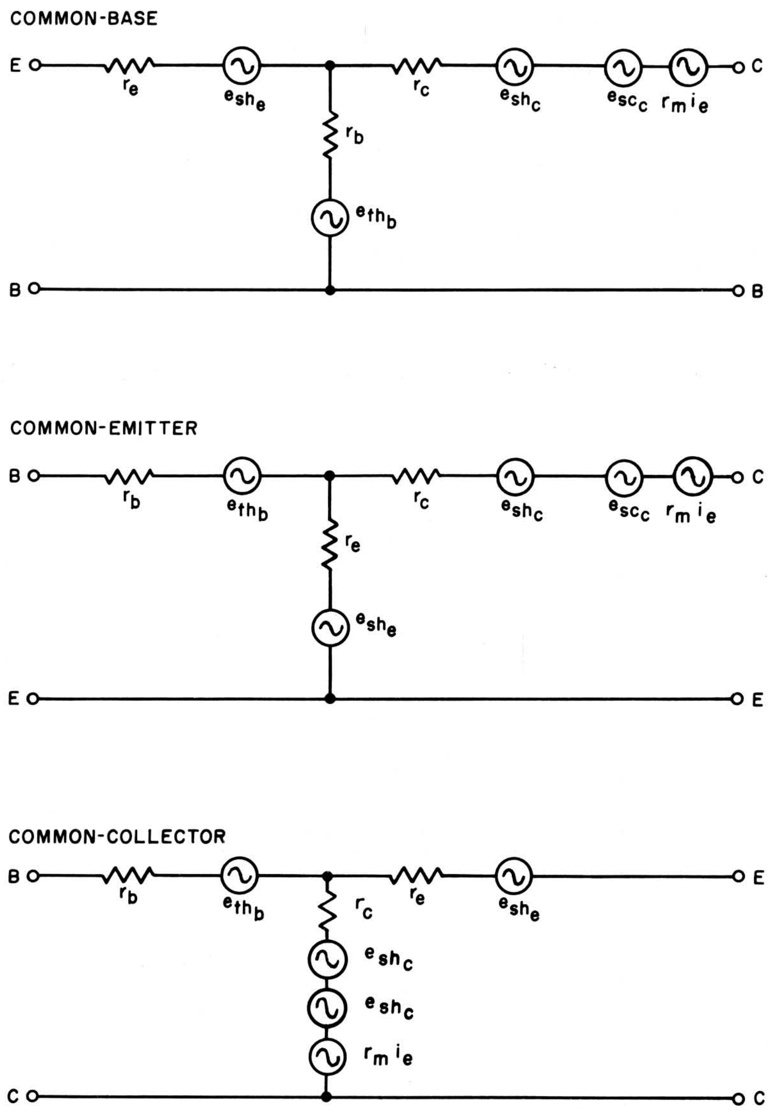


FIGURE 13. BASIC TRANSISTOR EQUIVALENT CIRCUITS WITH SEPARATION OF NOISE GENERATORS.

When a generator of internal resistance R_g and a load R_L' are connected to the equivalent circuits the resultant expressions for the single frequency noise factors are respectively:

Common-Base

$$F = 1 + \frac{1}{4KTR_g}\left[\overline{e^2_{sh_e}} + \overline{e^2_{th_b}}\left(\frac{ar_c - r_e - R_g}{ar_c + r_b}\right)^2 + \overline{e^2_{sh_c}}\left(\frac{r_e + r_b + R_g}{ar_c + r_b}\right)^2 + \overline{e^2_{sc_c}}\left(\frac{r_e + r_b + R_g}{ar_c + r_b}\right)^2\right] \qquad (30)$$

Common-Emitter

$$F = 1 + \frac{1}{4KTR_g}\left[\overline{e^2_{th_b}} + \overline{e^2_{sh_e}}\left(\frac{ar_c + r_b + R_g}{ar_c - r_c}\right)^2 + \overline{e^2_{sh_c}}\left(\frac{r_e + r_b + R_g}{ar_c - r_e}\right)^2 + \overline{e^2_{sh_c}}\left(\frac{r_e + r_b + R_g}{ar_c - r_e}\right)^2\right] \quad (31)$$

Common-Collector

$$F = 1 + \frac{1}{4KTR_g}\left[\overline{e^2_{th_b}} + \overline{e^2_{sh_e}}\left(\frac{r_e + r_b + R_g}{r_c}\right)^2 + \overline{e^2_{sh_c}}\left(\frac{r_b + R_g}{r_c}\right)^2 + \overline{e^2_{sc_c}}\left(\frac{r_b + R_g}{r_c}\right)^2\right] \quad (32)$$

Comparing Equations (30, 31, 32) with equation (5) it is noted that it is respectively:

Common-Base

$$\begin{cases} \overline{e^2_{ni}} = \overline{e^2_{sh_e}} + \overline{e^2_{th_b}} \\ \overline{e^2_{no}} = \overline{e^2_{th_b}} + \overline{e^2_{sh_c}} + \overline{e^2_{sc_c}} \end{cases} \quad (33)$$

Common-Emitter

$$\begin{cases} \overline{e^2_{ni}} = \overline{e^2_{th_b}} + \overline{e^2_{sh_e}} \\ \overline{e^2_{no}} = \overline{e^2_{sh_e}} + \overline{e^2_{sh_c}} + \overline{e^2_{sc_c}} \end{cases} \quad (34)$$

Common-Collector

$$\begin{cases} e_{ni} = \overline{e^2_{th_b}} + \overline{e^2_{sh_c}} + \overline{e^2_{sc_c}} \\ \overline{e^2_{no}} \quad \overline{e^2_{sc_c}} + \overline{e^2_{sh_c}} + \overline{e^2_{sh_e}} \end{cases} \quad (35)$$

To obtain numerical values from equations (30, 31, 32) it is necessary to write all the noise voltages explicitly following equations (29), (28) and (26) yielding:

$$e^2_{th_b} = 4KT\, r_{bb'} \quad (36)$$

$$\overline{e^2_{sh_e}} = 2eI_e r_e^2 \quad (37)$$

$$\overline{e^2_{sh_c}} = 2eI_{co}\, r_c^2 \tag{38}$$

$$\overline{e^2_{sc_c}} = k_c V^a R_c^\beta f^{-a} \tag{39}$$

Note that in equation (38) the thermal equilibrium current I_{co} is used instead of I_c in order to correctly separate the shot noise components from the two junctions, and that the intrinsic base resistance $r_{bb'}$ is used.

The above results could have been obtained also starting from the basic equation (5) which is rewritten below in a slightly different form.

$$F = 1 + \frac{1}{4KT\,R_g} \left| \overline{e^2_{ni}} + \overline{e^2_{no}}/\mu^2 \right| \tag{40}$$

where:

$$\mu = \frac{r_{21}}{r_{11} + R_g}$$

is the open circuit voltage gain. To express separately the three contributions to F one can write three noise factors:

$$\text{Thermal Noise Factor} = F_{th} = 1 + \frac{r^*_{11}}{R_g} + \frac{r^*_{22}}{\mu^2 R_g} \tag{41}$$

$$\text{Equivalent Shot Noise Factor} = F_{sh} = 1 + \frac{er^{2*}_{11}}{2KT\,R_g} I_1 + \frac{er^{2*}_{22}}{2KT\,R_g\mu^2} I_2 \tag{42}$$

$$\text{Semiconductor Noise Factor} = F_{sc} = 1 + \frac{1}{4KT\,R_g} \left[k_1 V_1^a R_1^\beta f^{-\gamma} + \frac{k_2 V_2^a R_2^\beta f^{-\gamma}}{\mu^2} \right] \tag{43}$$

where:

$e = 1.6 \times 10^{-19}$ coulombs
$K = 1.38 \times 10^{-23}$ joules/degree Kelvin
T = degrees Kelvin
R_g = generator resistance, ohms
V_1, I_1 = d-c input voltage and current
V_2, V_2 = d-c output voltage and current
α, β, γ = semiconductor noise coefficients, refer to equation (25)

The symbol * indicates that part of the resistance which is involved in the noise generation.

Considering the combined effect of equations (41), (42) and (43) the total noise figure is:

$$F = 1 + (F_{th} - 1) + (F_{sh} - 1) + (F_{sc} - 1) \tag{44}$$

which checks with equations (30, 31, 32) if:

$r^*_{11} = r_{bb'}$ in Equation 41
$r^*_{22} = 0$
$r^*_{11} = r_e$ in Equation 42
$r^*_{22} = r_c$
$I_1 = I_e$
$I_2 = I_{co}$

and the first term in the bracket of equation (43) = 0.

When the equations for the noise voltages (36), (37), (38) and (39) are substituted in equations (30), (31), and (32), the equations for noise factor may be put in a more usable form. Further, if certain assumptions are made, for example, $r_c \gg R_g$, $r_c \gg r_b$, $r_c \gg r_e$ the equations may be simplified and become:

Common-Base

$$F = 1 + \frac{r_{bb'}}{R_g} + \frac{r_e}{2R_g}\left[1 + \frac{I_{co}}{I_e}\left(\frac{r_e + r_b + R_g}{\alpha r_e}\right)^2\right] + \frac{k_c V_c^{\alpha} R_c^{\beta} f^{-\gamma}}{4KT R_g}\left(\frac{r_e + r_b + R_g}{\alpha r_c + r_b}\right)^2 \tag{45}$$

Common-Emitter

$$F = 1 + \frac{r_{bb'}}{R_g} + \frac{r_e}{2R_g}\left[1 + \frac{I_{co}}{I_e}\left(\frac{r_e + r_b + R_g}{r_e}\right)^2\right] + \frac{k_c V_c^{\alpha} R_c^{\beta} f^{-\gamma}}{4KT R_g}\left(\frac{r_e + r_b + R_g}{\alpha r_c - r_e}\right)^2 \tag{46}$$

Common-Collector

$$F = 1 + \frac{r_{bb'}}{R_g} + \frac{r_e}{2R_g}\left[1 + \frac{I_{co}}{I_e}\left(\frac{r_b + R_g}{r_e}\right)^2\right] + \frac{k_c V_c^{a} R_c^{\beta} f^{-\gamma}}{4KT\,R_g}\left(\frac{r_b + R_g}{r_c}\right)^2 \tag{47}$$

The usefulness of the above expressions resides mainly in the fact that it is possible to obtain from them minimum values of noise factor when the last term expressing semiconductor noise in the output junction is dropped; then the lower limits are dictated only by thermal noise from the base spread resistance and by shot noise from the input and output junctions.

Substituting typical values for the other quantities:

$$\begin{aligned} I_e &= 10^{-3} \text{ amperes} \\ r_e &= 26 \text{ ohms} \\ r_{bb'} &= 300 \text{ ohms} \\ r_b &= 350 \text{ ohms} \\ a &= 0.98 \\ I_{co} &= 4 \times 10^{-6} \text{ amperes} \\ R_g &= 500 \text{ ohms} \end{aligned}$$

it is found that the noise factor should be about 2.4 db. This minimum value for noise factor could further be reduced for transistors with lower values of I_{co} and $r_{bb'}$.

Identical results are obtained when using equations (12), (13), and (14) by substituting values of e_{ne} and e_{nc}; typical values in quiet RCA-2N34 transistors are:

$$\begin{aligned} e_{ne} &= (5 \text{ to } 40) \times 10^{-9} \text{ volts} \\ e_{nc} &= (10 \text{ to } 40) \times 10^{-6} \text{ volts} \end{aligned}$$

for normal operating conditions at $V_c = -6$ V, $I_c = -1$ma at 1 Kc over a 1 cycle noise bandwidth.

The agreement between theoretical and measured values of noise factor is satisfactory for transistors operating under conditions where the contribution of semiconductor noise is negligible.

Observed discrepancies from 1 to 2 db may be attributed to two factors:

1. the neglect of correlation among the various noise sources.
2. the omission of other noise mechanisms.

The latter point seems to be worthy of particular attention since it was recently disclosed that a mechanism of partition noise may be active in transistors.[11]

When this additional source is taken into account, a closer agreement between theory and experiment may be obtained.

EQUIVALENT INPUT NOISE RESISTANCE

An equivalent input noise resistance for a transistor may be deduced. This resistance, in effect, would be the series combination of equivalent noise resistances for thermal, shot, and semiconductor noise. In the case of the common base connection it is found:

Thermal Noise Equivalent Resistance

$$R_{th} = r_{bb'} \tag{48}$$

Emitter Shot Noise Equivalent Resistance

$$R_{sh_e} = \frac{r_e}{2} = \frac{e}{2}\,\frac{KT}{eI_e} \tag{49}$$

Collector Shot Noise Equivalent Resistance

$$R_{sh_c} = \frac{r_e}{2}\,\frac{I_{co}}{I_e}\left(\frac{r_e + r_b + R_g}{ar_e}\right)^2 \tag{50}$$

Collector Semiconductor Equivalent Resistance

$$R_{sc_c} = k_c V_c^{\alpha} R_c^{\beta} f^{-\gamma}\left(\frac{r_e + r_b + R_g}{ar_e}\right)^2 \tag{51}$$

A transistor amplifier can then be represented in the manner illustrated in Figure 14, where the emitter and collector junction equivalent shot noise resistances are combined into $R_{sh} = R_{sh_e} + R_{sh_c}$ Only the semiconductor noise equivalent resistance is frequency dependent; of the other two R_{th} is by its nature frequency independent, while R_{sh} can be considered constant within the audio range, although its behavior at high frequencies needs further investigation.

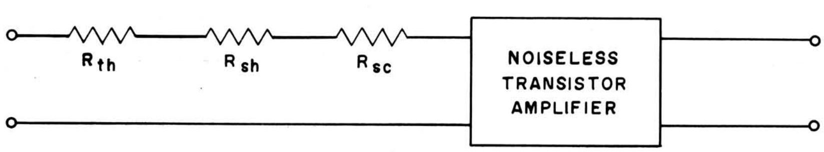


FIGURE 14. EQUIVALENT NOISE INPUT RESISTANCE IN A TRANSISTOR AMPLIFIER.

Using the same values for the transistor parameters given in a previous example, and again neglecting semiconductor noise, typical values for the equivalent noise resistances are:

R_{th} = 300 ohms
R_{sh_e} = 13 ohms
R_{sh_c} = 52 ohms

R equivalent noise = 365 ohms

It may be seen that the major contribution to noise is introduced by the thermal resistance $r_{bb'}$. An equivalent resistance for semiconductor noise is not calculated due to the lack of information concerning the value of some of the quantities appearing in the expression (51).

Once the equivalent input noise resistance is known, noise factor may be calculated as:

$$F = 1 + \frac{R \text{ equivalent noise}}{R_g} \tag{52}$$

It should be pointed out that the use of the preceding equations for the equivalent input noise resistance may lead to more expeditious calculations to be used by application engineers, however it must be noted that R_{sh_c} is also a function of R_g and therefore merely by increasing R_g in equation (52) will not minimize noise factor.

COMPARISON WITH VACUUM TUBES

A noticeable similarity is found in the general trend of the noise characteristics of vacuum tubes and transistors. The noise spectrum of a typical low noise triode (1620—triode connected) with an oxide coated cathode is shown in Figure 15. It may be observed that tube noise decreases at approximately 10 db per decade at lower frequencies (the "1/f" law) and then tends to approach an asymptotic value determined by shot noise.

That portion of the curve which is consistent with the "1/f" law is due to flicker effect in the cathode and produces a noise spectrum remarkably similar to that of semiconductor noise in transistors. Because of this flicker effect, results would certainly be in error if the noise formulas generally used for vacuum tubes at radio frequencies were extended down to the low frequency range. With certain oxide coated cathodes, flicker noise produces in effect appreciable components extending up to 20 Kc.

The similarity in the trend of vacuum tube and transistor noise in the audio frequency region is apparent when Figures 15 and 6 are compared. The similarity extends itself further into those respective frequency ranges where the contributions of shot noise remain constant. Eventually the noise factor increases with increasing frequency because of gain reduction.

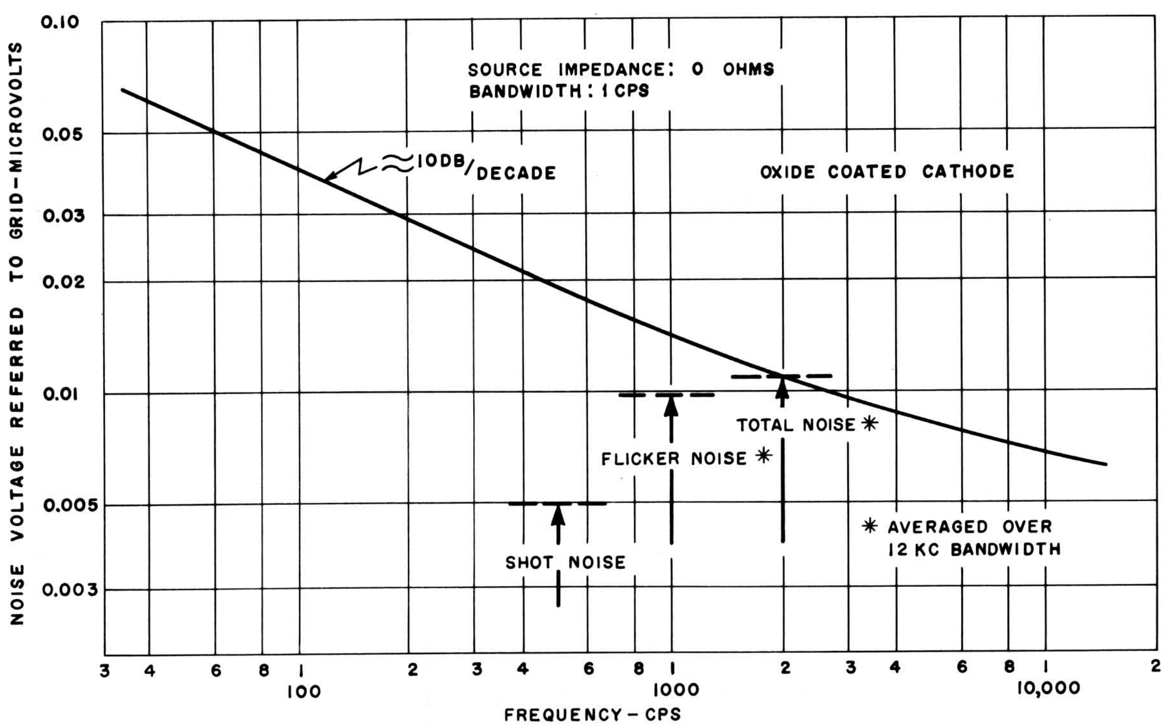


FIGURE 15. TRIODE TUBE NOISE VS. FREQUENCY.

The similarity is summarized in the following table:

Frequency Range	Noise Factor VS Frequency	Tube Noise	Transistor Noise
Very low	inversely proportional	flicker	semiconductor
Intermediate	constant	shot	shot and thermal
High	constant within certain limits, beyond which it increases indefinitely	shot, input conductance, transit time, reduced gain	shot and thermal transit time, reduced gain

For a vacuum tube, noise factor improves as the source impedance increases and zero db noise factor can be approached in practice. As a result, efficient input transformers greatly improve the noise factor of a system with a low source impedance such as offered by magnetic pickups and microphones. On the other hand, as shown in Figures 7 and 8, transistor noise factor is a minimum when working from a source impedance of about 500 ohms.

Figure 16 shows a direct comparison of transistor and tube noise plotted versus source resistance. It may be seen that transistors behave favorably in those cases where the generator impedance is low, thus it might be desirable to use transistors thereby eliminating an expensive input transformer.

It must be pointed out however that whereas the lower limit of transistor noise factor is determined by shot and thermal noise, in vacuum tubes the noise factor can be made to approach zero by driving the device with a high source resistance thus minimizing the noise contribution from the equivalent noise input resistance. Such a possibility does not seem to exist in transistors because of the finite value of the input resistance of the device.

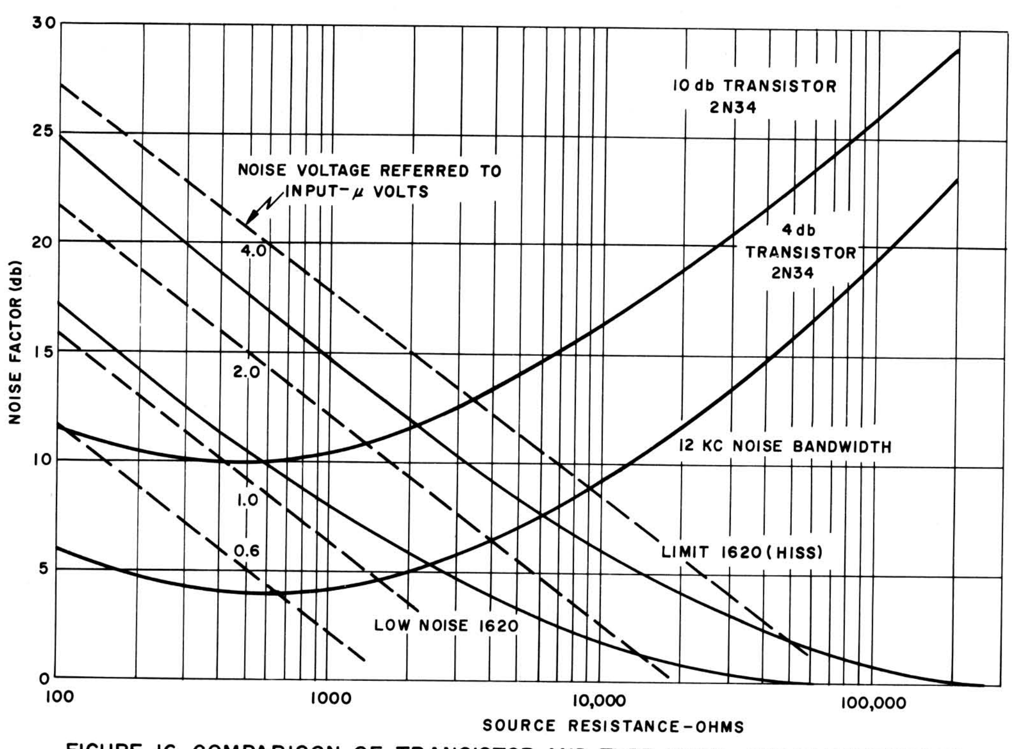


FIGURE 16. COMPARISON OF TRANSISTOR AND TUBE NOISE CHARACTERISTICS
NOISE FACTOR VS. SOURCE RESISTANCE

CASE OF COMPLEX SOURCE IMPEDANCE

Sometimes the question arises as to what should be done to obtain optimum noise factor in the case of a generator having a complex internal impedance.

The answer to this question is obtainable from equation (5) in the sense that the minimum value of noise factor will be obtained when the modulus of the generator internal impedance is:

$$|Z_g| = \sqrt{|Z_{11}|^2 + \rho|Z_{21}|^2}$$

where as usual:

$$\rho = \left(\frac{E_{ni}}{E_{no}}\right)^2$$

This means that the modulus of the generator internal impedance should equal the values given for the pure resistive case.

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