SOME NOTES ON NOISE THEORY AND ITS APPLICATION TO INPUT CIRCUIT DESIGN*†

By

Wm. A. Harris

Tube Department, RCA Victor Division,
Harrison, N. J.

Summary—The mechanism by which noise is produced in an electron tube and the relation between induced grid noise and plate noise are discussed. An equivalent circuit with noise generators supplying voltages and currents to simulate noise derived from the plate current of a tube, from the grid by passage of this current, and from the input circuit is then analyzed to determine the optimum noise factor obtainable under various conditions. The frequency for which the quantity $R_{eq}\ g_{in}$ is unity is seen to be an appropriate figure of merit for the noise produced by an electron tube. The frequencies corresponding to chosen values for the noise factor are presented for several receiving tube types. The paper concludes with a discussion of the circuit requirements which must be satisfied in order to obtain noise factors approximating the theoretical values.

Introduction

NOISE generated in the first tube of a receiving system is frequently the factor controlling the over-all sensitivity of the system. An understanding of the mechanism by which such noise is produced is helpful in the design of receiving equipment, particularly with respect to the choice of tube types. If the electrons in a tube were to leave the cathode at a perfectly uniform rate, there would be no noise, or at least, none in the frequency range in which a tube is useful. The rate of emission of electrons, however, is not uniform. In any given interval of time there are probably a few more or a few less electrons leaving the cathode than the average number for that amount of time. The classical shot-effect derivations predict the magnitudes of fluctuations of this sort. Furthermore, because theory and experimental data have revealed the extent to which space-charge effects can reduce these fluctuations in electron tubes, the noise components of the plate current of a tube can be computed in many instances.[1]

At high frequencies, the fluctuation current induced in the grid of

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[1] B. J. Thompson, D. O. North, and W. A. Harris, "Fluctuations in Space-Charge-Limited Currents at Moderately High Frequencies", *RCA Review*, Vol. IV: No. 3, pp. 69-285, January 1940; No. 4, pp. 443-473, April, 1940; Vol. V: No. 1, pp. 106-124, July, 1940; No. 2, pp. 244-260, October, 1940; No. 3, pp. 371-388, January, 1941; No. 4, pp. 505-524, April, 1941; Vol. VI, No. 1, pp. 114-124, July, 1941.

a tube by the passage of the fluctuating plate current through the grid is another noise source which must be considered. The magnitude of the mean square of this current is proportional to the component of input conductance due to transit time.[2]

Since the grid noise and plate noise are derived in part from the same current fluctuations, they cannot be treated as entirely independent noise sources. Nevertheless, valuable working formulas and principles have been derived for conditions under which coherence between grid noise and plate noise can be ignored.[3] It is possible, moreover, that the improvements obtainable by taking coherence into account are not very important for the majority of tubes and circuits in current use. Theoretical considerations, however, indicate that a substantial improvement in noise factor may be obtained by taking advantage of the coherence between grid noise and plate noise if the conditions assumed for the theory can be realized in actual tubes. Experimental evidence shows that at least part of this improvement can be obtained in a practical system.[4]

In this paper, the relation between induced grid noise and plate noise is illustrated by an examination of the result of the passage of a single electron through a tube. Then, the conditions giving optimum noise factors are derived, using the methods employed by Herold and others. Herold[3] showed that the noise factor for a tube is a function of the product $R_{eq}\, g_{in}$, where R_{eq} is the equivalent noise resistance and g_{in} is the input conductance. In this paper, the frequency for which the product $R_{eq}\, g_{in}$ is unity is recommended as an appropriate noise "figure of merit" for a tube. The ratios of the operating frequencies to this reference frequency therefore can be used as the abscissas for curves of optimum noise factor.

Current Impulses from One Electron

Figure 1 shows the distribution of potential in a parallel-plate triode. The potential curve is based on the assumption of a Maxwellian distribution of initial velocities, with a cathode temperature of approximately 1000 degrees Kelvin. The dotted curve represents the velocity of an electron with just enough initial velocity to allow it to pass the point of minimum potential and continue to the anode. The time of

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[2] D. O. North and W. R. Ferris, "Fluctuations Induced in Vacuum-Tube Grids at High Freqencies", *Proc. I.R.E.*, Vol. 29, pp. 49-50, February 1941.

[3] E. W. Herold, "An Analysis of the Signal-to-Noise Ratio of Ultra-High-Frequency Receivers", *RCA Review*, Vol. VI, No. 3, pp. 302-331, January, 1942.

[4] M. J. O. Strutt and A. vanderZeil, "Signal-Noise Ratio at VHF", *Wireless Engineer*, Vol. 23, pp. 241-249, September, 1946.

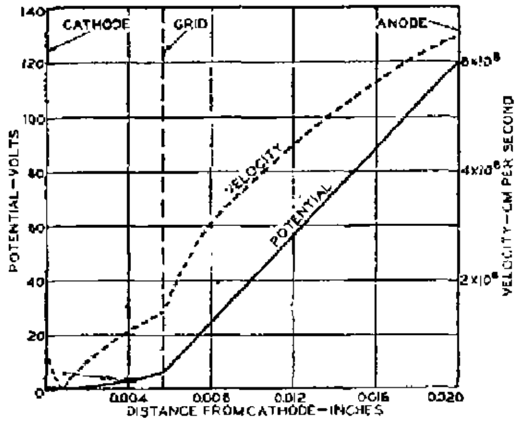

Fig. 1—Potentials and velocities in a parallel-plane triode.

transit for such an electron can be computed by a graphical integration process.

When a charge is in motion between two electrodes in a tube, current flows between the electrodes bounding the region containing the charge. For a parallel-plane structure this current is proportional to the velocity of the charge and inversely proportional to the distance between the two plane boundaries; it does not depend on the position of the charge relative to the boundaries.[5] The velocity curve of Figure 1 is applicable for a charge of the indicated initial velocity. If the velocities for various points in the cathode-grid space are divided by the distance between cathode and grid, and the velocities for various points in the grid-anode space are divided by the distance between grid and anode, quantities proportional to the current due to the motion of the charge for these various positions are obtained. Then, the relation between position and time obtained by integration may be used to obtain a current-time curve.

The curves of current versus time for the tube structure of Figure 1 are shown in Figure 2. The solid curve shows the current to the grid and the dotted curve the current to the plate which would result from the passage of one electron. The choice of the velocity of the slowest electrons which can reach the anode leads to a computation difficulty; the time required for such electrons to pass the potential-minimum region is theoretically infinite. Consequently, transit times are computed from the cathode to a point near the potential minimum on the cathode side, and from the grid back to a point near the potential minimum on the grid side. The three rectangles between the ends of the two curves show the times and currents for charges passing between the terminal points of these curves with velocities exceeded by 90, 50, or 10 per cent of the electrons reaching the anode. The use of one of these velocities would cause some change in the remainder of the curve, both in the current and the time scale, but the shape of the curve would be about as shown. The effect of a change in initial velocity on the current between grid and anode would be almost negligible. The cathode-to-grid transit time for an electron with an initial velocity

[5] S. Ramo, "Currents Induced by Electron Motion", *Proc. I.R.E.*, Vol. 27, pp. 584-585, September, 1939.

corresponding to one of the rectangles in Figure 2 is, therefore, approximately the sum of the transit times represented by the two curves and the appropriate rectangle. The indicated range is from 6 to 8×10^{-10} seconds. The transit time from grid to anode for the conditions of Figure 2 is about 1×10^{-10} seconds.

The curve of Figure 2 does not show the compensating effect which takes place when an extra charge passes through a tube. The potential minimum is depressed by an amount depending on the position of the added charge, during the whole time this charge is between cathode and grid. The result is a reduction of the current, which can be considered equivalent to the passage of a series of charges of opposite sign between potential minimum and grid, and the passage of charges of the same sign but of opposite direction between potential minimum and cathode. These effects account for the shot-effect reduction factor computed by North[1]. It appears, however, that between the initiating pulse and the compensating current there is some time delay which may be important in the determination of the noise at very high frequencies.

As soon as the extra noise-producing charge leaves the cathode a small effect on the minimum potential will be noted; some electrons which are reaching the potential minimum at this instant turn back instead of continuing toward the plate. The effect of the extra charge persists until it reaches the grid. The compensating effect cannot be completed until the time at which an electron, turned back because of the depression of the potential minimum when the extra charge was near the grid, would have reached the grid had it not been turned back.

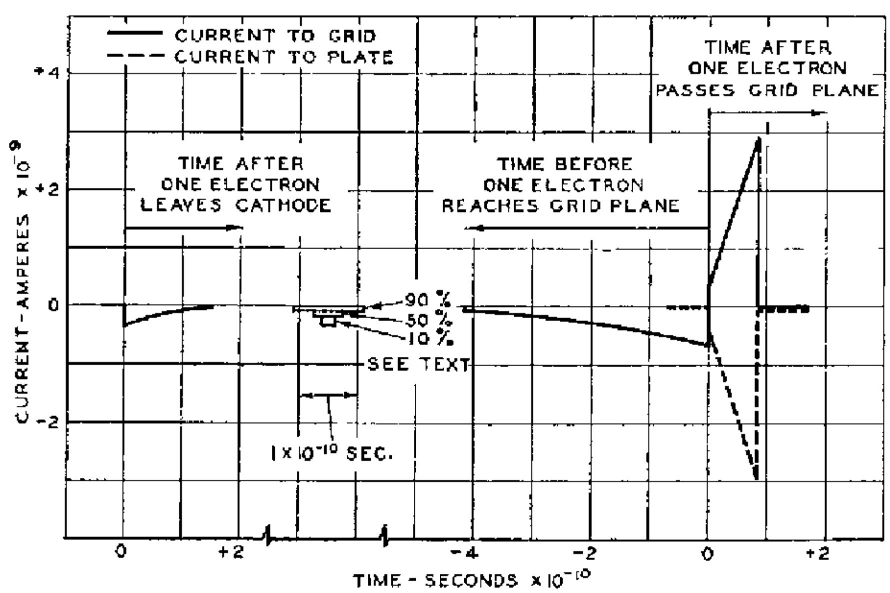

Fig. 2—Grid and plate currents due to passage of a single electron.

The compensating charges in motion after the passage of the causing charge, however, must themselves have an effect on the minimum potential. The complete result, consequently, is probably of the nature of a damped oscillation with a period related to the transit time of an electron from cathode to grid. Thus, the curves of Figure 2 do not present a complete picture of the generation of noise in a parallel-plane triode, but they do show some of the characteristics of the basic noise impulses.

It is pertinent at this point to discuss the extent to which grid and plate noise currents can be made to cancel each other. The pulse shapes are quite different, so it is evident that complete cancellation cannot be expected. Partial cancellation may be obtained if a voltage is developed at the grid by allowing the grid current to flow into a capacitor. This voltage is proportional to the integral of the grid current and has the effect of momentarily reducing the plate current. A suitable choice of capacitor value can give a plate-current pulse of zero net area for electrons of a particular initial velocity. However, there will always be some conductance in the grid circuit which will result in a grid-voltage component tending to increase the noise output. Moreover, electrons leaving the cathode with velocities too low to allow them to pass the point of minimum potential produce pulses of grid current without producing corresponding plate-current pulses.

Determination of Frequency Spectra

The curves of Figure 3 illustrate the method by which the frequency spectra corresponding to the grid-current and plate-current pulses may be obtained. The current which could be measured in the small frequency range represented by $d\omega$ at a frequency $\omega/2\pi$ is obtained from the Fourier integral:

$$A\,d\omega = \frac{2}{\pi}\int F_{(\lambda)} \cos \omega\lambda \, d\lambda \cos \omega t \, d\omega + \frac{2}{\pi}\int F_{(\lambda)} \sin \omega\lambda \, d\lambda \sin \omega t \, d\omega. \tag{1}$$

The function $F_{(\lambda)}$ represents the pulse.

When the frequency is low in comparison with the reciprocal of the transit time, the value of the term $\cos \omega\lambda$ in Equation (1) is nearly constant over the region in which $F_{(\lambda)}$ has a value other than zero. In addition, the value of the term $\sin \omega\lambda$ in Equation (1) can be represented as a straight line with a slope directly proportional to the frequency over the same region.

Because the grid pulse has equal positive and negative areas, the

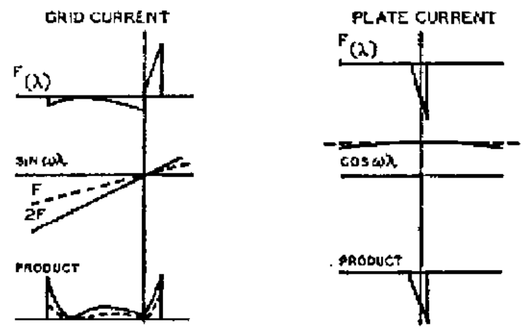

Fig. 3—Development of frequency spectra.

integral containing the cosine terms is zero for any frequency low enough so that cos $\omega\lambda$ can be considered constant. The integral containing the sine terms will have a value which is represented graphically by the area under the curve labeled "product" in the grid-current curves of Figure 3. This area will be directly proportional to the frequency because the slope of the sin $\omega\lambda$ line is proportional to frequency. It will also be proportional to transit time because, if the areas and shapes of the parts of the $F_{(\lambda)}$ curve are maintained constant and the base line is extended, the area under the "product" curve will increase in proportion to the increase in base-line length.

The plate pulse will give a zero value for the integral containing sine terms if a suitable point of origin is chosen. The integral containing cosine terms, then, gives the current, which is independent of the frequency when the frequency is low. Because the area of the plate-current pulse represents the amount of charge producing the pulse, the current in a small frequency band resulting from a given amount of charge is also independent of the transit time.

The mean-square noise current measurable in any frequency band results from large numbers of pulses distributed at random with respect to time. For the plate current, consequently, the mean-square current $d\overline{i^2}$ in a frequency band of width df can be represented by the equation

$$d\overline{i^2} = k_2\, df \qquad (2)$$

and for the grid current, by

$$d\overline{i^2} = k_1\, \omega^2\, \tau^2\, df \qquad (3)$$

where τ is the transit time, or

$$d\overline{i^2} = k_1\, \theta^2\, df \qquad (3a)$$

where θ is the transit angle.

The electronic component of input conductance is proportional to the square of the transit angle[6], so a proportionality between the mean-square noise current and the input conductance is indicated, thus:

$$d\overline{i^2} = k_3\, g_1\, df. \qquad (4)$$

North and Ferris[2] found that the complete relation for grid-current noise is

$$d\overline{i^2} = \theta_1\, g_1 \cdot 4k\, T_o\, df \qquad (5)$$

[6] D. O. North, "Analysis of the Effects of Space Charge on Grid Impedance", *Proc. I.R.E.*, Vol. 24, pp. 108-136, January, 1936.

where θ_1 has a numerical value of approximately 5 when the cathode temperature is 1000 degrees Kelvin and the reference temperature T_o is approximately 300 degrees Kelvin. The dependence on temperature is discovered only when the analysis is extended to include the compensating currents.

The plate current noise from a tube may be represented as if it were derived from a noise voltage at the grid sufficient to produce the noise current. The appropriate equations[1] are $d\overline{e^2} = 4kT\, R_{eq}\, df$ (6)

where, for oxide-coated cathode tubes, theory indicates approximately that, for triodes,

$$R_{eq} = 2.5/g_m \tag{7}$$

and for pentodes

$$R_{eq} = \frac{I_b}{I_b + I_{c2}} \left(\frac{2.5}{g_m} + \frac{20\, I_{c2}}{g_m^{\,2}} \right) \tag{8}$$

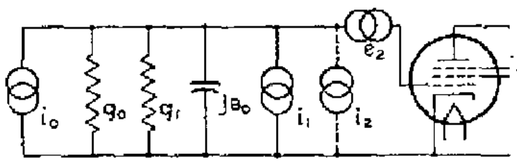

Fig. 4—Equivalent circuit.

Circuit Analysis

The circuit of Figure 4 represents the replacement of a real tube by a fictitious noise-free tube with zero input admittance and suitable noise generators and external circuit elements. The plate noise is introduced by a constant-voltage generator delivering a voltage e_2 in series with the grid. The noise current to the grid, i_1, is represented by a constant-current generator across the grid circuit. The noise from the input system, i_o, is represented by a second constant-current generator. The plate-noise generator can be replaced by another constant-current generator; the voltage output of the plate-noise generator is multiplied by the total admittance of the input circuit to give the required current i_2. The relations between the noise currents and the tube and circuit parameters are given by the equations:

$$e_2 = K\sqrt{R_{eq}} \tag{9}$$

$$i_1 = (-j)\, K\sqrt{\theta_1 g_1} \tag{10}$$

$$i_2 = e_2(g_o + g_1 + j\,B_o) = K\sqrt{R_{eq}}(g_o + g_1 + j\,B_o) \tag{11}$$

$$i_o = K\sqrt{\theta_o g_o}. \tag{12}$$

where $K = \sqrt{4kT\Delta f}$

g_1 is the electronic component of input conductance;

R_{eq} is the resistance equivalent for the plate noise, referred to the grid;

θ_1 is a multiplier relating grid noise to input conductance; its value is approximately 5 for tubes with oxide-coated cathodes;

θ_o is a multiplier representing the ratio of antenna noise to the noise in a resistor at room temperature;

g_o is the antenna conductance, referred to the grid;

B_o is the net susceptance of the circuit at the operating frequency.

It is assumed that the conductance g_o can be varied arbitrarily by some such means as a variable-ratio transformer between antenna and grid. Also, it is assumed that means such as a tuning capacitor are provided so that B_o can be varied arbitrarily. Ohmic losses in the input circuit are neglected.

The quantity $(-j)$ in parenthesis in the expression for i_1 indicates that i_1 may be in quadrature with e_2 over a specified frequency range. The preceding discussion suggests that this assumption is legitimate in the case of a triode, when the frequency is not too high and the frequency band is not too wide. The assumption is not valid, however, for a pentode because in that case the larger part of the plate noise results from the division of current between plate and screen grid[1], and consequently it cannot be correlated with the grid noise.

The total mean-square current from the three generators of Figure 4 can be found as follows: Add i_1 and i_2, taking coherence, if assumed, into account. Then, determine the sum of the squares of i_o, the real part of $(i_1 + i_2)$, and the imaginary part of $(i_1 + i_2)$. When coherence is not assumed, simply add the mean-square values of i_o, i_1, and i_2. The results follow:

When a quadrature relation between grid and plate noise is assumed, the mean-square current is

$$\overline{i^2} = K^2\{g_o\theta_o + R_{eq}(g_1 + g_o)^2 + (B_o\sqrt{R_{eq}} - \sqrt{\theta_1 g_1})^2\} \qquad (13)$$

When no coherence is assumed

$$\overline{i^2} = K^2\{g_o\theta_o + R_{eq}(g_1 + g_o)^2 + R_{eq}B_o^2 + \theta_1 g_1\} \qquad (14)$$

Optimum Noise Factors

Optimum performance with respect to noise is obtained when the term $g_o\theta_o$ is as large as possible in comparison with the other terms.

and, in fact, the noise factor as defined by North[7], Friis[8], and others is obtained by dividing Equation (13) or (14) by $K^2 g_o \theta_o$ and assuming $\theta_o = 1$. The first step in finding conditions for minimum noise is the adjustment of B_o to eliminate the term in which it appears in either equation.

Then, either equation can be differentiated with respect to the ratio g_1/g_o and an optimum value of noise factor can be obtained. The noise factors after adjustment of B_o are given by the equation

$$NF = 1 + R_{eq}\, g_1 \left(\frac{g_1}{g_o} + \frac{g_o}{g_1} + 2\right) \qquad (15)$$

when coherence is assumed, and the equation

$$NF = 1 + R_{eq}\, g_1 \left(\frac{g_1}{g_o} + \frac{g_o}{g_1} + 2\right) + \theta_1 \frac{g_1}{g_o} \qquad (16)$$

when coherence is not assumed.

The minimum noise factors, with the conditions for obtaining them are

$$NF = 1 + 4\, R_{eq}\, g_1 \quad (17) \qquad \frac{g_1}{g_o} = 1 \quad (18) \qquad B_o^2 = \theta_1 g_1^2 / R_{eq}\, g_1 \quad (19)$$

when coherence is assumed; and, when coherence not assumed

$$NF = 1 + 2\, R_{eq}\, g_1 + 2\sqrt{\theta_1 R_{eq}\, g_1 + (R_{eq}\, g_1)^2} \qquad (20)$$

$$\frac{g_1}{g_o} = \sqrt{R_{eq}\, g_1 / (\theta_1 + R_{eq}\, g_1)} \quad (21) \qquad B_o = 0 \quad (22)$$

The quantities R_{eq} and g_1 are both tube parameters Since they appear as the product $R_{eq}\, g_1$ in Equations (17) and (20), the magnitude of this product indicates the noise performance obtainable from a tube. The quantity g_1, however, varies with the square of the frequency. For purposes of computation, it is preferable to use as a reference parameter the square root of the product $R_{eq}\, g_1$, which

[7] D. O. North, "The Absolute Sensitivity of Radio Receivers", *RCA Review*, Vol. VI, No. 3, pp. 332-343, January, 1942.

[8] H. T. Friis, "Noise Figures of Radio Receivers", *Proc. I.R.E.*, Vol. 32, pp. 419-422, July, 1944.

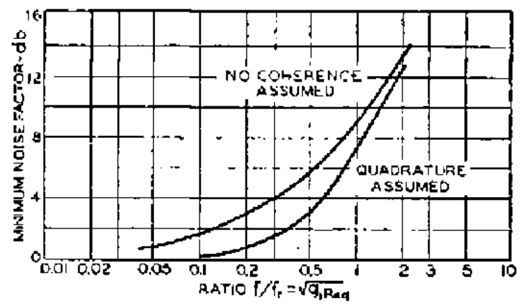

Fig. 5—Minimum noise factor.

varies with the first power of the frequency. The curves of Figure 5 show the optimum noise factors for the two cases considered, plotted against the quantity $\sqrt{R_{eq}\, g_1}$ for the condition $\theta_1 = 5$. If the frequency for which $\sqrt{R_{eq}\, g_1}$ is unity is designated as f_n, the quantity $\sqrt{R_{eq}\, g_1}$ for any frequency f is equal to the ratio f/f_n.

The method of analysis described above is essentially the same as that used by Herold[3]. The curve for the case of no coherence (Figure 5) can be identified with one of the curves (Figure 5) of Reference 3 when differences in the coordinates used are taken into account. Equation (21), giving the required ratio of tube input conductance to circuit conductance, is equivalent to Equation (7) of Reference 3.

The susceptance required for the case of quadrature, as found from Equation (19), is obtained by the same amount of capacitance at any frequency. Equation (19) can be rewritten

$$B_o^2 = \theta_1 g_1 / R_{eq}. \tag{19a}$$

Because g_1 is proportional to the square of the frequency and R_{eq} and θ_1 are independent of frequency, it is evident that the susceptance B_o is directly proportional to the frequency and, consequently, can be produced by a fixed capacitance.

Comparison of Tubes

The data for Tables I and II were obtained by calculating values for the equivalent noise resistance and using measured values for input conductance for the tube types listed. Table I gives the reference frequency for noise, f_n, and the frequencies for which noise factors of 1, 3, and 10 decibels are calculated for a number of pentode types. No coherence is assumed between plate noise and grid noise for this case. Table II gives similar data for two triodes and for several pentodes, connected as triodes, under the alternate assumptions of no coherence between plate and grid noise, and a quadrature relation between plate and grid noise. The 10-decibel column for the quadrature case is omitted because the indicated frequencies are too high to make the assumption appear reasonable.

Table I—Pentodes

Type	R_{eq} ohms	g_{in} (100 mcs.) micromhos	f_n mcs.	Frequency for Noise Factor (1 db.) mcs.	(3 db.) mcs.	(10 db.) mcs.
6SK7	11,600	440	45	2.5	8.9	56
6AC7	650	1,730	94	5.3	19	119
6BA6	3,800	580	67	3.8	13.4	85
6AG5	1,900	300	133	7.5	27	169
6AK5	1,900	125	208	11.6	41	262
6BH6	2,360	340	122	6.8	24	154
6BJ6	3,800	275	98	5.5	19.3	124

The input conductance values used in Tables I and II were measured by the susceptance-variation method[9] and include the effects of lead inductance. For pentodes, the predominant lead effect is that of the cathode-lead inductance, which tends to increase the input conductance. For triodes, inductance in the plate lead tends to reduce the input conductance and this effect may be equal or greater than the effect of cathode-lead inductance. For the triode-connected pentodes, the input-conductance data obtained with the tubes connected as pentodes are used.

Triode "A" in Table II is a developmental triode, designed primarily for use as a high-frequency oscillator. The low input conductance and the consequent high "f_n" value recorded for this type

[9] "Input Admittance of Receiving Tubes", RCA Application Note AN-118, RCA Tube Department, Harrison, N. J., April, 1947.

Table II—Triodes and Triode-Connected Pentodes

				Frequency for Indicated Noise Factor				
				No Coherence Assumed			Quadrature Assumed	
Type	R_{eq} (Triode) ohms	g_{in} (100 mcs.) micromhos	f_n (Triode) mcs.	(1 db.) mcs.	(3 db.) mcs.	(10 db.) mcs.	(1 db.) mcs.	(3 db.) mcs.
6SK7.....	970	440	72	4.0	14	91	18	36
6AC7.....	214	1,730	164	9.2	33	207	41	82
6BA6.....	410	580	204	11.5	41	258	51	102
6AG5.....	380	300	294	17	59	374	74	148
6AK5.....	380	125	476	26	92	580	116	230
6BH6.....	390	340	274	15.4	54	345	68	137
6BJ6......	485	275	274	15.4	54	345	68	137
6J6.......	470	195	320	18.0	63	410	80	160
"A"*......	360	50	747	42	147	940	186	373

* Developmental triode.

is probably accounted for by close spacing, high current density, and a symmetrical cylindrical structure which contributes to uniformity in the cathode-to-grid and grid-to-plate transit times.

Relation of Reference Frequency to Transit Time

The reference frequency for noise for a triode depends primarily on the electron transit time between cathode and grid. The noise equivalent resistance for a triode is approximately $R_{eq} = 2.5/g_m$ (7)

and the electronic component of the input conductance[6] is approximately

$$g_1 = g_m(\omega\tau_1)^2/20. \tag{23}$$

The product, therefore, is

$$R_{eq}\, g_1 = (\omega\tau_1)^2/8. \tag{24}$$

This product is equal to unity when

$$\omega\tau_1 = 2.83 \tag{25}$$

$$\text{so} \quad f_n = 0.45/\tau_1. \tag{26}$$

The values of f_n obtained from Equation (26) are even higher than the values given in Table II. The cathode-to-grid transit time for a tube such as Type 6AK5 is of the order of 7×10^{-10} seconds, so the value of f_n from the above equation is

$$f_n = 0.064 \times 10^{-10} \text{ cycles} = 640 \text{ megacycles.}$$

The value obtained for Type 6AK5 from input conductance data (Table II) is 476 megacycles.

It appears that the only way to increase the frequency for a given noise factor with electron tubes of conventional design is to reduce the transit time. Triode types such as the 6J6, 6J4, and 2C43 are designed with close enough spacings and, consequently, short enough transit times to give promise of good results in equipment designed for minimum noise.

Effect of Circuit Losses

An important question with reference to the application of the curves and tables presented is the attainability of the circuit conditions assumed. The conditions are not hard to realize in practice, as the following examples illustrate:

1. Consider the use of Type 6AK5 as a pentode amplifier at 40 megacycles. The reference frequency f_n is 208 megacycles, so the ratio f/f_n is 0.192; the product $R_{eq}\, g_1$ is 0.037. The calculated noise factor is 3 decibels. The required ratio g_1/g_a is 0.046. Because the tube input conductance for 40 megacycles is 19.7 micromhos, the required antenna loading is 230 micromhos. For a tube input capacitance of 6 micromicrofarads, the quantity ωC is 1500 micromhos; because

the total conductance at the grid is 250 micromhos, the minimum value of Q is 6. Higher Q values may be obtained by adding more capacitance with appropriate inductance values. It is evident that there will be no serious increase in the noise factor until the conductance of the added elements becomes appreciable in comparison with 250 micromhos. If the Q is improved to 50 by addition of a resonant circuit with a Q of 200, the added conductance is approximately 60 micromhos. The noise factor would be increased from 3 to 3.5 decibels by the added circuit losses.

2. Consider the 6AK5 or an equivalent tube connected as a triode used at 200 megacycles. Neutralization may be used to avoid feedback, but feedback generally does not have an important effect on the question of obtainable noise factors. The reference frequency f_n is 476 megacycles; the ratio f/f_n is 0.42; the expected noise factors, from the two curves of Figure 5, are 5.1 decibels for no coherence, 2.3 decibels if the quadrature relation holds. In the first case, the required antenna loading is 2600 micromhos and the resulting Q for the input circuit is only 2. Adjustment of Q to any moderate desired value can be made by the addition of circuit elements as before without materially affecting the noise factor. In the second case, the antenna loading would be adjusted to equality with the tube conductance, which is 500 micromhos for this frequency. Then, the susceptance which must be added is 5700 micromhos, corresponding to a capacitance of 4.6 micromicrofarads.

CONCLUSIONS

The conclusions which may be drawn from this discussion may be summarized as a set of principles to be followed in the design of amplifiers for low noise.

1. Choose an input tube with low transit time. For frequencies above 30 megacycles, use a triode or a triode-connected pentode.

2. Adjust the input circuit with signal-to-noise ratio as the criterion. This adjustment is most readily made by using a noise generator, such as a diode, as a signal source.

3. Try the effect of detuning the input from resonance and the effect of increasing the coupling to the antenna beyond the value for maximum gain.

When theoretical considerations indicate a very low noise factor, it may be necessary to pay considerable attention to the design of the load circuit of the first tube and the input circuit for the second tube to obtain optimum results.