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RCA RADIOTRON DIVISION

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APPLICATIONS NOTES

APPLICATION NOTE ON INPUT LOADING OF RECEIVING TUBES AT RADIO FREQUENCIES

The input resistance of an r-f amplifier tube may become low enough at high radio frequencies to have appreciable effect on the gain and selectivity of a preceding stage. Also, the input capacitance of a tube may change enough with change in avc bias to cause appreciable detuning of the grid circuit. It is the purpose of this Note to discuss these two effects and to show how the change in input capacitance can be reduced.

Input Conductance

In this Note, it is convenient to discuss the input loading of a tube in terms of the tube's input conductance, rather than input resistance. The input conductance, g_i, of commercial receiving tubes can be represented approximately by the equation

$$g_i = k_c f + k_h f^2 \qquad (1)$$

where f is the frequency of the input voltage. A table of values of k_c and k_h for several r-f tube types is shown on the next page. The approximate value of a tube's input conductance in micromhos at all frequencies up to those in the order of 100 megacycles can be obtained by substituting in Eq. (1) values of k_c and k_h from the table. In some cases, input conductance can be computed for conditions other than those specified in the table. For example, when all the electrode voltages are changed by a factor n, k_h changes by a factor which is approximately $n^{-1/2}$. The value of k_c is practically constant for all operating conditions. Also, when the transconductance of a tube is changed by a change in signal-grid bias, k_h varies directly with transconductance over a wide range. In the case of converter types, the value of k_h depends on oscillator-grid bias and oscillator voltage amplitude. In converter and mixer types, k_h is practically independent of oscillator frequency.

Table of Approximate Values k_c and k_h for Several Tube Types

Tube Type	Heater Volts	Plate Volts	Screen Volts	Signal-Grid Bias Volts	Suppressor Volts	k_c Micro-mhos/Mc	k_h Micro-mhos/Mc^2
6A8	6.3	250	100	-3	---	0.3	-0.05*
6J7	6.3	250	100	-3	0	0.3	0.05
6K7	6.3	250	100	-3	0	0.3	0.05
6K8	6.3	250	100	-3	---	0.3	-0.08†
6L7	6.3	250	100	-3	---	0.3	0.15X
6SA7 (Self-excited)	6.3	250	100	0	---	0.3	-0.03#
6SA7 (Separately excited)	6.3	250	100	-2	---	0.3	-0.03#
6SJ7	6.3	250	100	-3	0	0.3	0.05
6SK7	6.3	250	100	-3	0	0.3	0.05
954	6.3	250	100	-3	0	0.0	0.005
1851	6.3	250	150	-2	0	0.3	0.13
1852	6.3	250	150	-2	0	0.3	0.13
1853	6.3	250	200	-3	0	0.3	0.065

* For oscillator-grid current of 0.3 ma. through 50000 ohms.
† For oscillator-grid current of 0.15 ma. through 50000 ohms.
X For wide range of oscillator-grid currents.
For grid No. 1 current of 0.5 ma. through 20000 ohms.

In Eq.(1), the term $k_c f$ is a conductance which exists when cathode current is zero. The term $k_h f^2$ is the additional conductance which exists when cathode current flows. These two terms can be explained by a simple analysis of the input circuit of a tube.

Cold Input Conductance

The input impedance of a tube when there is no cathode current is referred to as the cold input impedance. The principal components of this cold impedance are a resistance due to dielectric hysteresis, and a reactance due to input capacitance and cathode-lead inductance. Because these components are in a parallel combination, it is convenient to use the terms admittance, the reciprocal of impedance, and susceptance, the reciprocal of reactance. For most purposes, the effect of cathode-lead inductance is negligible when cathode current is very low. The cold input admittance is, therefore, a conductance in parallel with a capacitive susceptance. The conductance due to dielectric hysteresis increases linearly with frequency. Hence, the cold input conductance can be written as $k_c f$, where k_c is proportional to the power factor of grid insulation and is the k_c of Eq.(1).

Hot Input Conductance

The term $k_h f^2$, the input conductance due to the flow of electron current in a tube, has two principal components, one due to electron transit time and the other due to inductance in the cathode lead. These two components can be analyzed with the aid of Fig.1. In this circuit, C_h is the capacitance between grid and cathode when cathode current flows, C_g is the input capacitance due to capacitance between grid and all other electrodes except cathode, g_t is the conductance due to electron transit time, and L is the cathode-lead inductance. Inductance L represents the inductance of the lead between the cathode and its base pin, together with the effect of mutual inductances between the cathode lead and other leads near it. Analysis of the circuit of Fig.1 shows that, with L small as it generally is, the input conductance, g_h, due to the presence of cathode current in the tube, is approximately

$$g_h = g_m \omega^2 L C_h + g_t$$

where $\omega = 2\pi f$. The term $g_m \omega^2 L C_h$ is the conductance due to cathode-lead inductance. It can be seen that this term varies with the square of the frequency. In this term, g_m is the grid-cathode transconductance because the term is concerned with the effect of cathode current flowing through L. In a pentode, and in the 6L7, this transconductance is approximately equal to the signal-grid-to-plate transconductance multiplied by the ratio of d-c cathode current to d-c plate current. In the converter types 6A8, 6K8, and 6SA7, the signal-grid-to-cathode transconductance is small. Cathode circuit impedance, therefore, has little effect on input conductance in these types.

For an explanation of the conductance, g_t, due to electron transit time, it is helpful to consider the concept of current flow to an electrode in a tube. It is customary to consider that electron current flows to an electrode only when electrons strike the surface of the electrode. This concept, while valid for static conditions, fails to account for observed high-frequency phenomena. A better concept is that, in a diode for example, plate current starts to flow as soon as electrons leave the cathode. Every electron in the space between cathode and plate of a diode induces a charge on the plate; the magnitude of the charge induced by each electron depends on the proximity of the electron to the plate. Because the proximity changes with electron motion, there is a current flow to the plate through the external circuit due to the motion of electrons in the space between cathode and plate.

Consider the action of a conventional space-charge-limited triode as shown in Fig.2. In this triode, the plate is positive with respect to cathode and the grid is negatively biased. Due to the motion of electrons between cathode and grid, there is a current I_a flowing into the grid. In addition, there is another current I_b flowing out of the grid due to the motion of electrons between grid and plate receding from the grid. When no alternating voltage is applied to the grid, I_a and I_b are equal and the net grid current (I_g) is zero.

Suppose, now, that a small alternating voltage (e_g) is applied to the grid. Because the cathode has a plentiful supply of electrons, the charge represented by the number of electrons released by the cathode (Q_k) is in phase with the grid voltage, as shown in Figs.3a and 3b. The charge induced on the grid (Q_g) by these electrons would also be in phase with the grid voltage if the charges released by the cathode were to reach the plane of the grid in zero time, as shown in Fig.3c. In this hypothetical case, the grid current due to this induced charge (Fig.3d) leads the grid voltage by 90 degrees, because by definition, current is the time rate at which charge passes a given point. However, the charge released by the cathode actually propagates toward the plate with finite velocity; therefore, maximum charge is induced on the grid at a time later than that corresponding to maximum grid voltage, as shown in Fig.3e. This condition corresponds to a shift in phase by an angle θ of Q_g with respect to e_g; hence, the grid current lags behind the capacitive current of Fig.3d by an angle θ, as shown in Fig. 3f. Clearly, the angle θ increases with frequency and with the time of transit τ. Expressed in radians, $\theta = \omega\tau$.

The amplitude of Q_g is proportional to the amplitude of the grid voltage; the grid current, which is the time rate of change of Q_g, is thus proportional to the time rate of change of grid voltage. For a sinusoidal grid voltage, $e_g = E_g \sin\omega t$, the time rate of change of grid voltage is $\omega E_g \cos\omega t$. Therefore, for a given tube type and operating point, the amplitude of grid current is

$$I_g = KE_g\omega$$

and the absolute value of grid-cathode admittance due to induced charge on the grid is

$$Y_t = \frac{I_g}{E_g} = K\omega \qquad (3)$$

The conductive component (g_t) of this admittance is

$$g_t = Y_t \sin\theta = Y_t\theta = K\omega\theta \quad \text{(for small values of } \theta\text{)}$$

Because $\theta = \omega\tau$, this conductance becomes, for a given operating point,

$$g_t = K\omega^2\tau \qquad (4)$$

Thus, the conductance due to electron transit time also varies with the square of the frequency. This conductance and the input conductance, $g_m\omega^2 LC_h$, due to cathode-lead inductance, are the principal components of the term $k_h f^2$ of Eq.(1).

This explanation of input admittance due to induced grid charge is based on a space-charge-limited tube, and shows how a positive input admittance can result from the induced charge. The input admittance due to induced grid charge is negative in a tube which operates as a temperature-limited tube, that is, as a tube where cathode emission does not increase when the potential of other electrodes in the tube is increased. The emission of a tube operating with reduced filament voltage is temperature limited; a tube with a screen interposed between cathode and grid acts as a temperature-limited tube when the screen potential is reasonably high. The existence of a negative input admittance in such a tube can be explained with the aid of Fig.4.

When the value of E_{c2} in Fig.4 is sufficiently high, the current drawn from the cathode divides between G_2 and plate; any change in one branch of this current is accompanied by an opposite change in the other. As a first approximation, therefore, it is assumed that the current entering the space between G_2 and G_3 is constant and equal to ρv, where ρ is the density of electrons and v is their velocity. G_2 may now be considered as the source of all electrons passing to subsequent electrodes.

Suppose, now, that a small alternating voltage is connected in series with grid G_3, as shown in Fig.4. During the part of the cycle when e_g is increasing, the electrons in the space between G_2 and G_3 are accelerated and their velocities are increased. Because the current (ρv) is a constant, the density of electrons (ρ) must decrease. In this case, therefore, the charge at G_2 is 180 degrees out of phase with the grid voltage, as shown at A and B of Fig.5. This diminution in charge propagates toward the plate with finite velocity and induces a decreasing charge on the grid. Because of the finite velocity of propagation, the maximum decrease in grid charge occurs at a time later than that corresponding to the maximum positive value of e_g, as shown in Fig.5c. The current, which is the derivative of Q_g with respect to time, is shown in Fig.5d. If there were no phase displacement ($\theta = 0$), this current would correspond to a negative capacitance; the existence of a transit angle θ, therefore, corresponds to a negative conductance. By reasoning similar to that used in the derivation of Eqs. 3 and 4, it can be shown that the absolute value of negative admittance due to induced grid charge is proportional to ω, and that the negative conductance is proportional to ω^2. These relations are the same as those shown in Eqs. 3 and 4 for the positive admittance and positive conductance of the space-charge-limited case.

A negative value of input conductance due to transit time signifies that the input circuit is receiving energy from the "B" supply. This negative value may increase the gain and selectivity of a preceding stage. If this negative value becomes too large, it can cause oscillation. A positive value of input conductance due to transit time signifies that the signal source is supplying energy to the grid. This energy is used in accelerating electrons toward the plate and manifests itself as additional heating of the plate. A positive input conductance can decrease the gain and selectivity of a preceding stage.

It should be noted that, in this discussion of admittance due to induced grid charge, no mention has been made of input admittance due to electrons between grid and plate. The effect of these electrons is similar to that of electrons between grid and cathode. The admittance due to electrons between grid and plate, therefore, can be considered as being included in Eq.(3).

Change in Input Capacitance

The hot grid-cathode capacitance of a tube is the sum of two components, the cold grid-cathode capacitance, C_c, which exists when no cathode current flows, and a capacitance, C_t, due to the charge induced on the grid by electrons from the cathode. The capacitance C_t can be derived from Eq. (3), where it is shown that the grid-cathode admittance due to induced grid-charge is

$$Y_t = K\omega$$

The susceptive part of this admittance is $Y_t\cos\theta$. Since this susceptance is equal to ωC_t, the capacitance C_t is

$$C_t = K\cos\theta = K \quad \text{(for small values of } \theta\text{)}$$

Hence, the hot grid-cathode capacitance C_h is

$$C_h = C_c + K$$

The total input capacitance of the circuit of Fig.1, when the tube is in operation, includes the capacitance C_h and a term due to inductance in the cathode lead. This total input capacitance, C_i, can be shown to be approximately

$$C_i = C_g + C_h - g_m g_t L \qquad (5)$$

where the last term shows the effect of cathode-lead inductance. This last term is usually very small. It can be seen that if this last term were made equal in magnitude to $C_g + C_h$, the total input capacitance would be made zero. However, the practical application of this fact is limited because g_m and g_t change with change in electrode voltages, and g_t changes with change in frequency.

When cathode current is zero, the total input capacitance is practically equal to $C_g + C_c$. Subtracting this cold input capacitance from the hot input capacitance given by Eq.(5), we obtain the difference, which is $K - g_m g_t L$. In general, K is greater than $g_m g_t L$. Therefore, in a space-charge-limited tube, where K is positive, the hot input capacitance is greater than the cold input capacitance. In a temperature-limited tube, where K is negative, the hot input capacitance is less than the cold input capacitance. In both tubes K changes with change in transconductance. Because of this change, the input capacitance changes somewhat with change in avc bias. In many receivers, this change in input capacitance is negligible because it is small compared to the tuning capacitances connected in the grid circuits of the high-frequency stages. However, in high-frequency stages where the tuning capacitance is small, and the resonance peak of the tuned circuit is sharp, change in avc bias can cause appreciable detuning effect.

Reduction of Detuning Effect

The difference between the hot and the cold input admittances of a space-charge-limited tube can be reduced by means of an unby-passed cathode resistor, R_k in Fig.6. The total hot input admittance of this circuit is made up of a conductance and a capacitive susceptance, $\omega C_i'$. Analysis of Fig.6 shows that, if cathode-lead inductance is neglected, the total hot input capacitance, C_i', is approximately

$$C_i' = C_g + C_c \frac{1 + K/C_c}{1 + g_m R_k} \qquad (6)$$

Inspection of this equation shows that if K is positive and varies in proportion with g_m, the use of the proper value of R_k will make C_i' independent of g_m. In a space-charge-limited tube, K is positive and is found by experiment to be approximately proportional to g_m. It follows that the proper value of R_k will minimize the detuning effect of avc in a space-charge-limited tube. Eq.(6) is useful for illustrating the effect of R_k but is not sufficiently precise for computation of the proper value of R_k to use in practice. This value can be determined by experiment. It will be found that this value, in addition to minimizing capacitance change, also reduces the change in input conductance caused by change in avc bias. The effect of unby-passed cathode resistance on the change in input capacitance and input conductance of an 1852 and 1853 is shown in Figs.7 and 8. These curves were taken at a frequency of 40 megacycles. The curves for the 1852 also hold good for the 1851.

It should be noted that, because of degeneration in an unby-passed cathode resistor, the use of the resistor reduces gain. The reduced gain is $1/(1 + g_mR_k)$ times the gain with the same electrode voltages but with no unby-passed cathode resistance. The hot input conductance of a tube with an unby-passed cathode resistor can be determined by modification of the values of k_h in the table on page 2. The value of k_h in the table should be multiplied by $g_m/(1 + g_mR_k)$. The resultant value of k_h, when substituted in Eq.(1), with k_c from the table, gives the input conductance of a tube with an unby-passed cathode resistor. In the factor, $(1 + g_mR_k)$, g_m is the grid-cathode transconductance when R_k is by-passed.

When an unby-passed cathode resistor is used, circuit parts should be so arranged that grid-cathode and plate-cathode capacitances are as small as possible. These capacitances form a feedback path between plate and grid when there is appreciable impedance between cathode and ground. To minimize plate-cathode capacitance, the suppressor and the screen by-pass condenser should be connected to ground rather than to cathode.

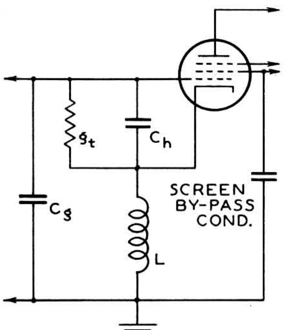

FIG. 1

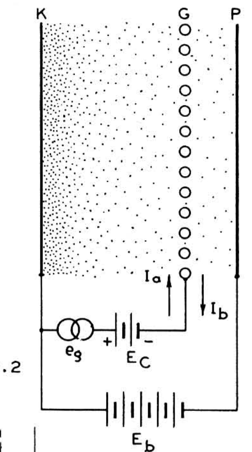

FIG. 2

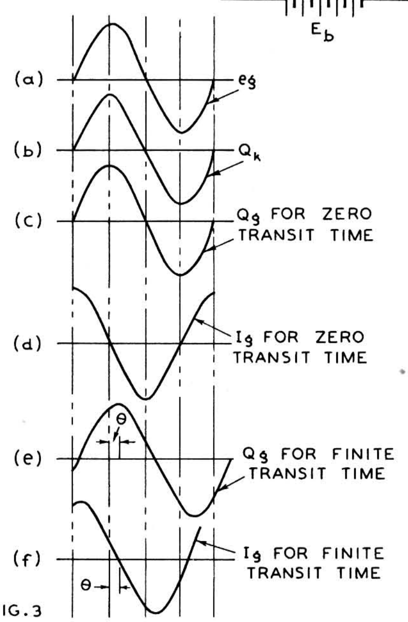

FIG. 3

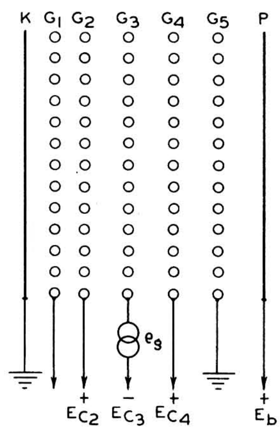

FIG. 4

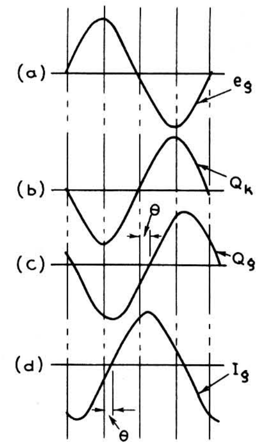

FIG. 5

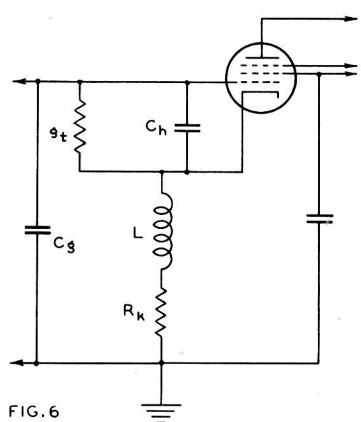

FIG. 6

1851, 1852

TYPICAL CHARACTERISTICS

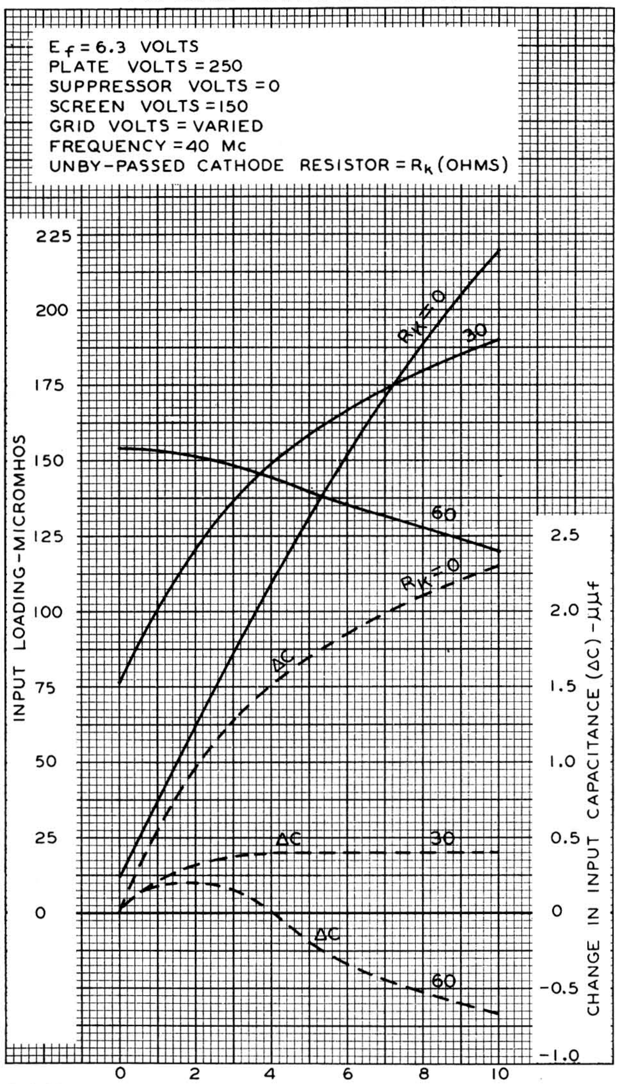

FIG.7

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1853

TYPICAL CHARACTERISTICS

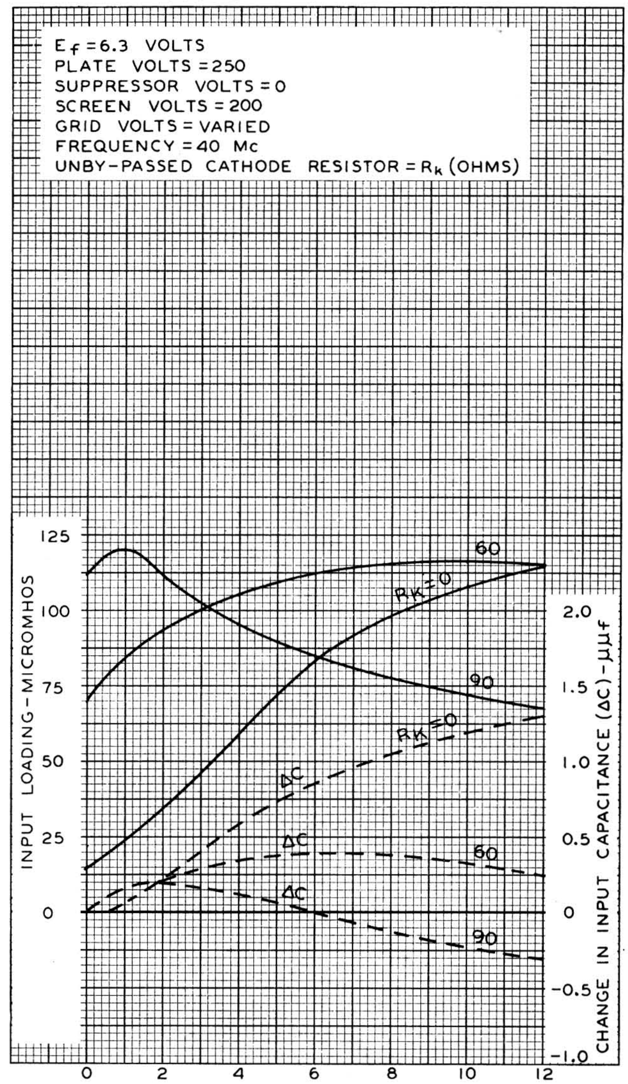

FIG.8

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