LB-1042

TRANSISTOR INPUT STAGE FOR PHONOGRAPH PICKUPS

RADIO CORPORATION OF AMERICA

RCA LABORATORIES

INDUSTRY SERVICE LABORATORY

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Approved

Stuart Wm Seeley

This bulletin describes several transistor circuits that are suitable as input stages for use with phonograph pickups. Circuits are given for both inductive and capacitive pickups. Noise, gain, and interchangeability are the factors that are considered in the circuit design.

General Considerations

Noise

There are three kinds of noise in a transistor[1], namely: white noise, 1/f surface noise, and 1/f leakage noise. The dominant mean square white noise generator is located between the intrinsic base, b', and the emitter, e, in the hybrid π equivalent circuit as shown in Fig. 1 and its noise power is proportional to the d-c base current. This noise is essentially the same for different transistors operating at the same d-c base current. The mean square 1/f surface noise power is proportional to the square of the d-c emitter current, and, as the term implies, is inversely proportional to frequency. In ordinary circuits, the dominant generator is also located between b' and e in the equivalent circuit and can also be represented by the current generator $\overline{i_{b'e}^{2}}$ in Fig. 1. There is a wide variation in the magnitude of this noise even among transistors of the same type. The mean square 1/f leakage noise is proportional to the square of the d-c leakage current. The latter is the leakage component of the open emitter collector back current, I_{co}, which is characterized by its voltage-dependency. The 1/f leakage noise generator is located between b' and c as shown in Fig. 1.

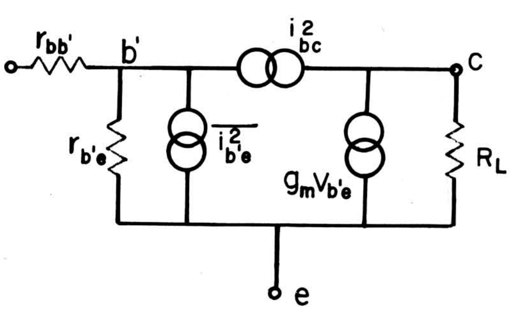

Fig. 1 – Noise current generators in the hybrid π equivalent circuit.

1. *RB-29 A Determination of 1/f Noise Sources in Semiconductor Diodes and Triodes by* W. H. Fonger.

Since both the white noise and the 1/f surface noise are proportional to the d-c operating current, it is desirable to use a low d-c current for low-noise operation. Depending upon whether the white noise or the surface noise dominates, the total noise power generally increases by 3 to 6 db for each 2-to-1 increase in d-c current if the leakage noise is negligible. Leakage noise depends on leakage current which in turn varies as the d-c collector voltage. For present-day transistors, the leakage noise is usually negligible if the collector-to-base potential is less than 10 volts.

External circuit impedance also plays an important role in the noise performance of a transistor stage. The impedance in series with the base should be small so that the noise current generator $\overline{i_{b'e}^{2}}$ is loaded down by the low base circuit impedance. The resultant noise voltage between b' and e is then reduced, giving a proportionately small output noise current from the collector. Assuming that $\overline{i_{b'e}^{2}}$ is the only noise generator, it can be shown that the signal-to-noise output current ratio for a base-input circuit as shown in Fig. 2a is equal to (as shown in the Appendix):

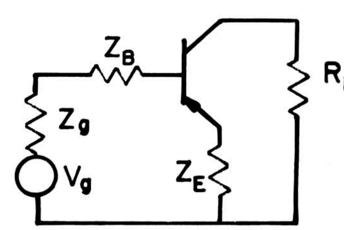

Fig. 2 – (a) Base input circuit.

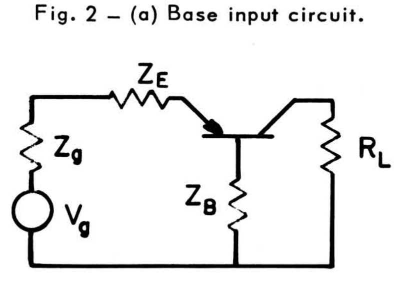

Fig. 2 – (b) Emitter input circuit.

$$\left(\frac{S}{N}\right)_i = \frac{V_g}{(Z_g + Z_B + Z_E)\ (\overline{i_{b'e}^{\,2}})^{1/2}} \qquad (1)$$

where V_g is the generator voltage, Z_g is the generator impedance, Z_B is the impedance in series with the base, including the base lead resistance, and Z_E is the impedance in series with the emitter. It can be shown that Eq. (1) also holds true for the signal-to-noise output current ratio for the emitter input circuit as shown in Fig. 2b. From Eq. (1) it can be seen that if an external impedance is connected in series with the base or the emitter (e.g., for equalizing the frequency response of a recording characteristics), the signal-to-noise ratio is degraded. The degradation becomes appreciable when the external impedance becomes greater than the generator impedance, Z_g. Note that Eq. (1) is independent of the current amplification factor, β, of the transistor used. If negative feedback is used and is shunt fed to the input terminal, the effect is equivalent to reducing β and hence, does not change the signal-to-noise ratio. If negative feedback is fed in series with the input, the effect is the same as increasing the external emitter impedance. So long as the effective emitter impedance is less than Z_g, there is little change in S/N. In general, negative feedback does not influence the signal-to-noise ratio. The application of these principles to actual input circuits will be illustrated later.

Frequency Response

The velocity response of a "New Orthophonic" (RIAA/NARTB) recording characteristic is shown in Fig. 3. This is the variation of voltage generated by an inductive pickup as a function of frequency. The asymptotic lines are shown as dotted lines. When a capacitive pickup is used, the generated voltage response is proportional to the displacement and is shown as the amplitude response curve. In order that the output current will have a flat frequency response, different compensating methods may be used as will be described later.

Distortion

Distortion is usually due to variation of the current amplification factor and/or the transconductance. The current amplification factor of a low-power transistor usually increases quite rapidly with increasing d-c emitter current at low currents, reaches a maximum in the neighborhood of one or two milliamperes, and decreases as the emitter current is further increased[2]. When a grounded-emitter transistor stage is driven from a high impedance source, the d-c emitter current should be chosen such that the variation of β with current is a minimum.

When a grounded emitter transistor stage is driven from a low impedance source, distortion may arise from variation of the transconductance at the signal rate. This variation may be caused by too low or too high an operating current.

In either case the distortion can be reduced by negative feedback. Shunt feedback is most effective in reducing distortion caused by β variation while series feedback is most effective in reducing distortion caused by transconductance variations.

2. *LB-917 On the Variation of Junction Transistor Current Amplification Factor With Emitter Current* by W. M. Webster.

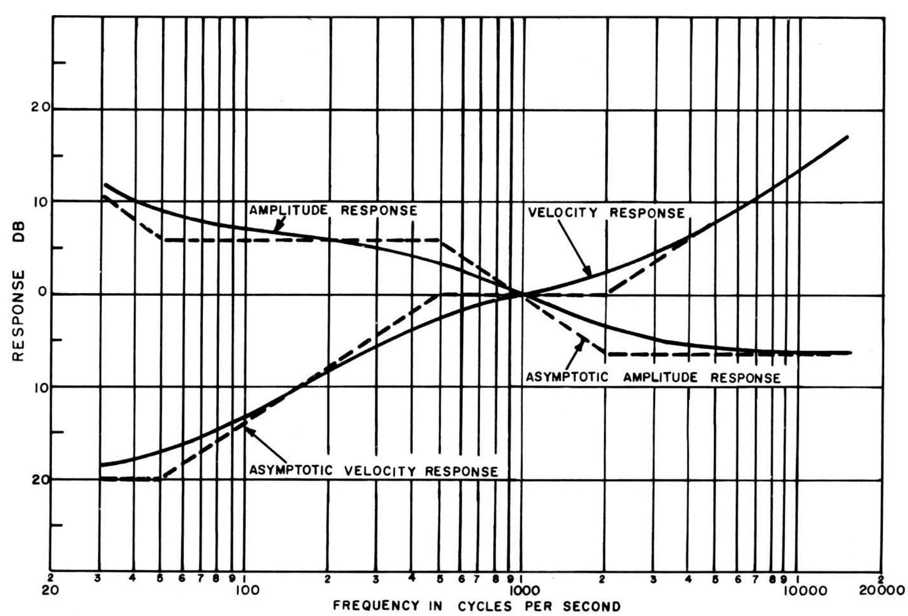

Fig. 3 – 'New Orthophonic' recording characteristics.

Output Current

The output current of a transistor is equal to the input current times the current amplification factor. When the input impedance is much greater than the generator impedance, the input current is inversely proportional to the input impedance, and a lower input impedance gives greater output current. However, in input circuits incorporating frequency equalization, the input impedance can not be lowered very far without affecting the flatness of the frequency response. The input impedance should therefore be chosen as a compromise between maximum output current and maximum flatness.

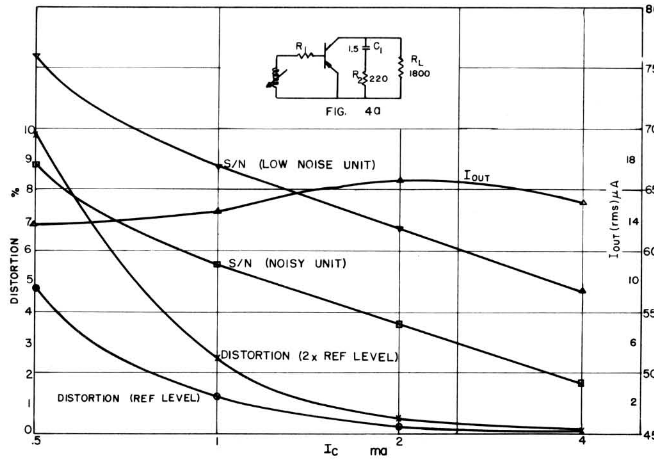

Fig. 4 – Circuit for inductive pickup and its characteristics.

Input Circuits

The foregoing considerations as applied to practical circuits will be illustrated in the following examples. These circuits are designed for use in conjunction with a variable reluctance pickup (RCA SPC-1 or G. E. RPX series) with R = 400Ω, L = 0.5 henries; or a crystal pickup (RCA 75575), with an equivalent series capacitance of 1000 $\mu\mu$fd. These are among the most commonly-used pickups. The circuit constants are adjusted at each operating current for maximum flatness in response from 30 cps to 15,000 cps. It should be kept in mind that considerably greater output current may be obtained if a somewhat narrower response is tolerable. In the noise measurements, two transistors were used having approximately the same current gain (β = 70 at I_C = 1 ma) but different noise figures. The noise figures of the two transistors were 12 db and 5 db with collector current = 0.5 ma, collector voltage = 4 volts, generator resistance = 1000Ω, load resistance = 20,000Ω, noise bandwidth = 1000 cps, mean frequency = 1000 cps.

Circuits for Inductive Pickups

Fig. 4a shows a suitable circuit. Batteries and base biasing network are not shown for simplicity. The input resistance is constant and equal to the inductive reactance of the pickup at 2000 cps. (7000 ohms for the RCA or G.E. reluctance pickup). The desired input resistance is obtained by connecting R_1 in series with the base. Although the induced voltage response of the pickup increases at 6 db/octave up to about 2000 cps, the dominant inductive reactance makes the input current response flat at all higher frequencies. The frequency response between 50 cps and 500 cps is equalized by means of a low-pass network, C_1 and R_2. For proper equalization, the reactance of C_1 is made approximately equal to R_L at 50 cps, the first cross-over frequency, and the reactance of C_1 is approximately equal to R_2 at 500 cps, the second cross-over frequency.

Since there is an external base resistance, R_1, which is greater than the source impedance below 2000 cps, the noise output is high. The signal-to-noise ratios of a noisy transistor and a low-noise transistor are plotted in Fig. 4b, using 12 millivolts at 1000 cps as a reference signal.* The distortion at low d-c collector current is quite high. The output current changes somewhat since β varies with I_C.

Another circuit for use with an inductive pickup is shown in Fig. 5. The input resistance of this circuit is the same as that of the previous circuit. The difference here is that the input resistance is obtained by reflecting the emitter resistance, R_3 in Fig. 5a, instead of using a resistance in series with the base. The value of R_3 in Fig. 5a is made equal to $1/\beta$ times R_1 of Fig. 4a. As explained previously in connection with Eq. (1), at frequencies where the source impedance is smaller than the input impedance the use of a lower external resistance

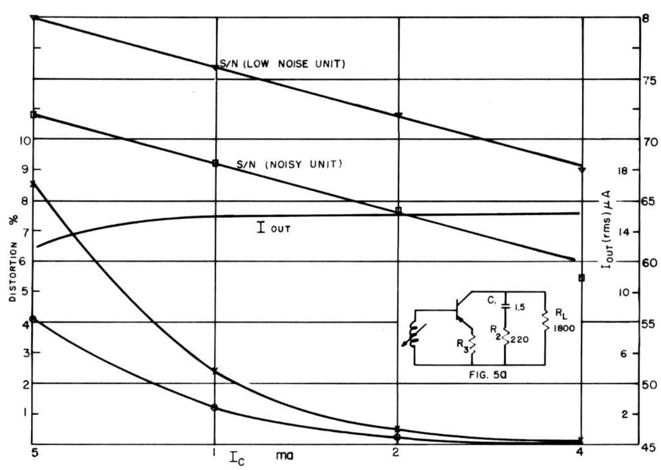

Fig. 5 – Second circuit for an inductive pickup and its characteristics.

* Test record (RCA-12/5/51) output using SPC-1 pickup.

as in this circuit greatly improves the signal-to-noise ratio. The measured signal-to-noise ratios are plotted in Fig. 5b. Note that they are about 10 db better than those of the previous circuit. The distortion and output currents of this circuit are approximately the same as the circuit of Fig. 4a. As far as interchangeability of transistors goes, the circuit of Fig. 4a can maintain a flat frequency response better than the circuit of Fig. 5a because the reflected input resistance of the latter is equal to r_{be} + βR_E, which will not be constant for different values of β.

A third circuit for use with inductive pickups is shown in Fig. 6a. In this circuit the low frequency equalization (50 to 500 cps) is obtained by means of negative feedback (note C_2 and R_4) instead of a low-pass filter. R_5 is used to lower the input resistance between the base and emitter to a value much lower than R_1 thereby maintaining nearly constant input impedance. For high operating collector current (say > 1 ma), r_{be} is small enough so that R_5 may not be needed. For proper equalization of Orthophonic characteristics:

$$\beta R_L \cong 1/2\pi \times 50 \times C_2$$

$$R_4 \cong 1/2\pi \times 500 \times C_2 \qquad (2)$$

$$R_1 \cong 2\pi \times 2000 \times L$$

where L is the inductance of the pickup.

Due to the resistance, R_1, used in series with the base, the noise output of this amplifier is high. As mentioned previously, negative feedback does not appreciably change the signal-noise-ratio, the overall noise should be approximately the same as in the first circuit. This is shown in the signal-to-noise curves in Fig. 6b. However, the use of negative feedback reduces the distortion, particularly at high frequencies where the amount of negative feedback is high. The reduction of output current at low d-c collector currents is due to R_5 which is used for maintaining a frequency response within ±1.5 db throughout the audio range. The low-frequency response of this circuit is affected by the value of β as is indicated by Eq. (2).

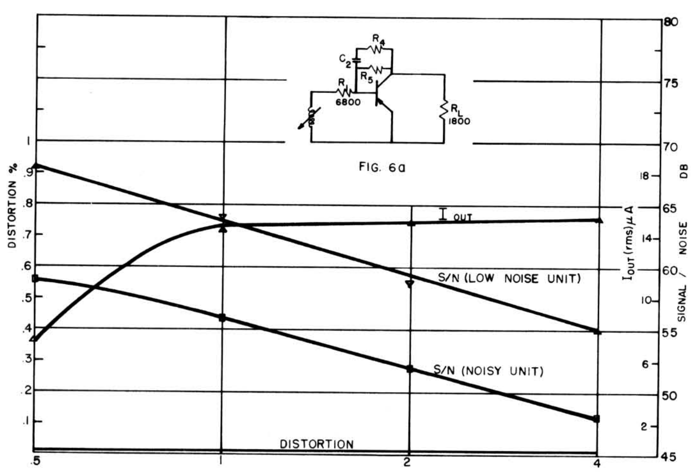

Fig. 6 – Third circuit for an inductive pickup and its characteristics.

Fig. 7a illustrates another circuit for use with inductive pickups. In this circuit, the input impedance increases with frequency in the same manner as the velocity response curve of the record. This is accomplished by negative feedback applied to the emitter of the first transistor. For $R_8 >> R_6$, the amount of feedback is equal to approximately β_2 times R_8/Z_F where β_2 is the β of transistor T_2 and Z_F is the impedance of the feedback

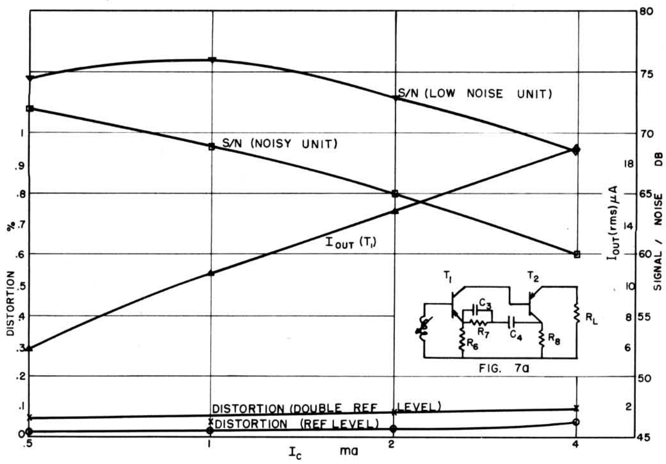

Fig. 7 – Fourth circuit for an inductive pickup and its characteristics.

network C_3, C_4 and R_7. The input impedance is equal approximately to $\beta_1 R_E$ times $(1 + \beta_2 R_8/Z_F)$, provided R_E is much greater than the internal emitter resistance, r_e, of the transistor ($\cong 0.025/I_C$). The frequency response deviates 3 db below 50 cps if R_E is made equal to r_e. For proper equalization,

$$\frac{1}{2\pi \times 50\ C_4} \cong \beta_2 R_8$$

$$\frac{1}{2\pi \times 500\ C_4} \cong R_7 \qquad (3)$$

$$\frac{1}{2\pi \times 2000\ C_3} \cong R_7$$

At any frequency the input impedance is much higher than the generator impedance of typical inductive pickups. Hence this circuit is independent of the pickup impedance, whereas all three preceding circuits must be used in conjunction with a pickup of predescribed impedance to obtain a flat frequency response. The absence of base resistance is beneficial to the noise performance. Since the effect of negative feedback can be taken as increasing the effective emitter resistance, $(R_E)_e$, and since the condition existing in the present circuit is $Z_g > (R_E)_e$ at any frequency, Eq. (1) indicates that the signal-to-noise feedback ratio should remain the same as if there were no degeneration, i.e., the same as the circuit of Fig. 5a. This is shown in Fig. 7b. The negative current feedback also reduces the distortion. At high d-c operating currents the output current of this circuit is equal or even higher than other preceding circuits. The reason is that at high currents r_e is low enough to permit the use of a low R_6. Once R_6 is lower than R_3 of Fig. 5a the output current of this circuit becomes higher. The results shown in Fig. 7b were obtained with $R_6 = 4r_e$. If R_6 is made equal to r_e, an increase of 12 db in the output signal can be expected with a deviation in response flatness at below 50 cps of 3 db.

Input Circuits For Capacitive Pickups

A circuit for use with capacitive pickups is shown in Fig. 8a. In this circuit the frequency equalization is obtained by connecting a high impedance network, R_9, R_{10}, C_5, in series with the base. For flat response the sum of R_9 and R_{10} is equal to the capacitive reactance of the pickup at 50 cps; R_{10} is equal to the reactance of C_5 at 500 cps; and R_9 is equal to the reactance of C_5 at 2000 cps. As the connection of high base impedance causes a high output noise current, this circuit has a poor signal-to-noise ratio, as shown in Fig. 8b. The distortion is high at low operating currents, reaches a minimum at moderate currents where the variation in β with respect to current is low, and increases somewhat at higher operating currents. The output signal current, also shown in Fig. 8b, is nearly the same as that of the

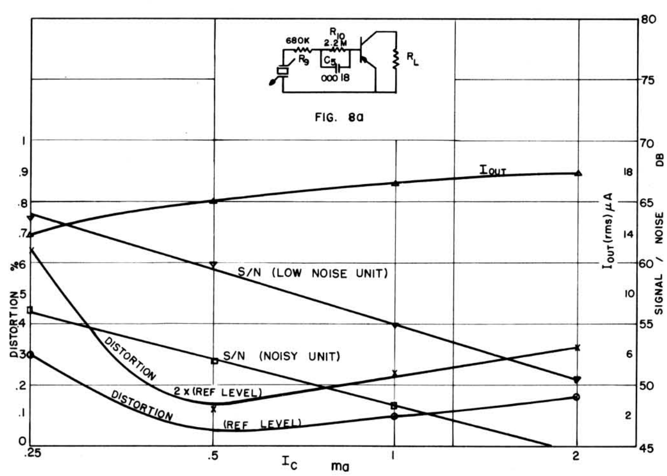

Fig. 8 – Circuit for capacitive pickup and its characteristics.

variable reluctance pickup. It is interesting to note that in vacuum tube amplifiers, variable reluctance pickups usually require one more stage than crystal pickups.

Another circuit for use with capacitive pickups is shown in Fig. 9a. This circuit differs from the previous circuit in that the frequency equalization is placed in series with the emitter instead of the base. The required impedance is equal to $1/\beta$ times that used in series with the base in the previous circuit. The use of a smaller external impedance greatly improves the signal-to-noise ratio as is shown in Fig. 9b. The equalizing network gives a high degree of negative current feedback. This kind of feedback reduces the distortion of the amplifier when a voltage generator is used, but does not reduce the distortion when there is an appreciable amount of generator impedance. Since the impedance of a crystal pickup increases at low frequencies, the distortion at low frequencies may be considerable (as shown in Fig. 9b).

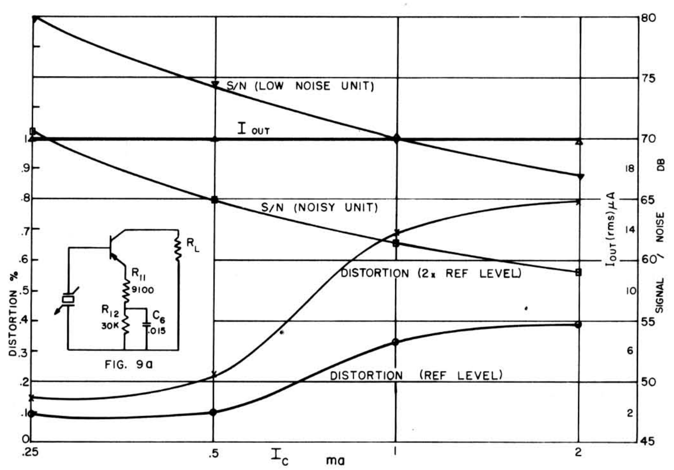

Fig. 9 – Second circuit for a capacitive pickup and its characteristics.

The high d-c voltage drop across the external emitter resistance present in the circuit of Fig. 9a may be reduced by connecting a capacitor, C_7, across the input as shown in Fig. 10a. Now the equivalent generator capacitance to which the base is connected is increased by $(C_7 + C_o)/C_o$, where C_o is the equivalent capacitance of the pickup. The required equalizing impedance in series with the emitter is also reduced by $(C_7 + C_o)/C_o$. The d-c voltage drop across R_{13} and R_{14} is therefore, much less than that across R_{11} and R_{12} in the previous circuit.

Although the input circuit loop impedance is reduced by $(C_7 + C_o)/C_o$, the equivalent generator voltage is also reduced the same amount. The resulting input current as well as the output current is therefore the same as in the previous circuit. Since the equivalent generator voltage, the equivalent source impedance, and the external emitter impedance are all reduced by the same factor, Eq. (1) indicates that the signal-to-noise ratio of this circuit will be the same as before (shown in Fig. 10b). Since this circuit has a lower source impedance the distortion is also lower.

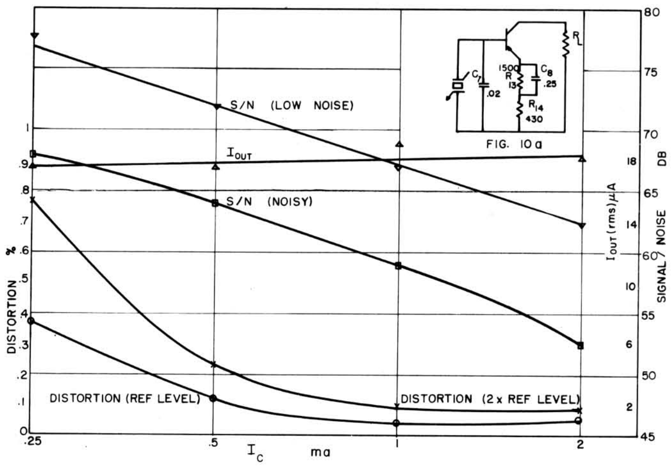

Fig. 10 – Third circuit for a capacitive pickup and its characteristics.

When the value of C_7 is made much greater than C_o, the equivalent source impedance is practically independent of C_o. Pickups with different values of C_o may be used without changing the equivalent source impedance and the frequency response of the amplifier. This is another advantage of this circuit.

Fig. 11a shows a circuit for capacitive pickups in which the input impedance is made much smaller than the source impedance and the current gain is made to vary inversely as the velocity response of the recording characteristics. These functions are obtained by means of negative feedback from the collector to the base. For proper compensation,

$$\begin{aligned} 1/2\pi \times 50\ C_9 &\cong \beta R_L \\ 1/2\pi \times 500\ C_9 &\cong R_{15} \\ 1/2\pi \times 2000\ C_{10} &\cong R_{15} \end{aligned} \tag{4}$$

As explained previously, series negative feedback does not change the signal-to-noise ratio of a transistor amplifier. As shown in Fig. 11b, the signal-to-noise ratios are about the same as that in the last two circuits. The negative feedback however reduces the distortion, particularly at high frequencies where the amount of feedback is great. The output current is proportional to the current gain and inversely proportional to the input circuit loop impedance. In this circuit both the current gain and the input circuit loop impedance are reduced. For instance, at 50 cps, the effective current gain and input circuit loop impedance are all reduced by the square root of two. The net result is that the output signal current is equal to the output current in the last three cases. This circuit also has the advantage that interchanging pickups of different C_o does not alter the frequency response, so long as the reactance of C_o is much greater than the input impedance at any frequency.

Judging from the different circuits just described, it appears that the preferred circuit for the variable reluctance pickup is that of Fig. 7a and for the crystal pickup is that of Fig. 11a. A complete phonograph amplifier circuit is shown in Fig. 12, using a modification of the input circuit of Fig. 7a in conjunction with the quasi-complementary circuit described in LB-1027[3].

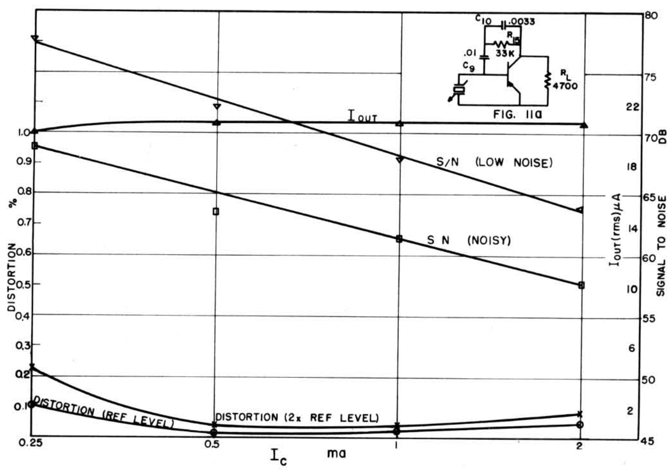

Fig. 11 – Fourth circuit for a capacitive pickup and its characteristics.

Discussion

In the foregoing examples, the pickups are all connected directly to the input. No input transformers are used. A signal-to-noise ratio of between 65 and 75 db is usually satisfactory for record reproduction. For maximum signal-to-noise ratio, Eq. (1) shows that external resistances should be kept to a minimum. Since $r_{bb'}$ constitutes a portion of Z_B, the maximum signal-to-noise ratio according to Eq. (1) is

$$\left(\frac{S}{N}\right)_i = \frac{V_g}{(Z_g + r_{bb'})\,(\overline{i_{b'e}^{\,2}})^{1/2}} \tag{5}$$

If, furthermore, an input transformer is used or the turns wound on the inductive pickup can be changed, there

3. *LB-1027 A Transistor Phonograph Amplifier Using A Quasi-Complementary Circuit* by H. C. Lin.

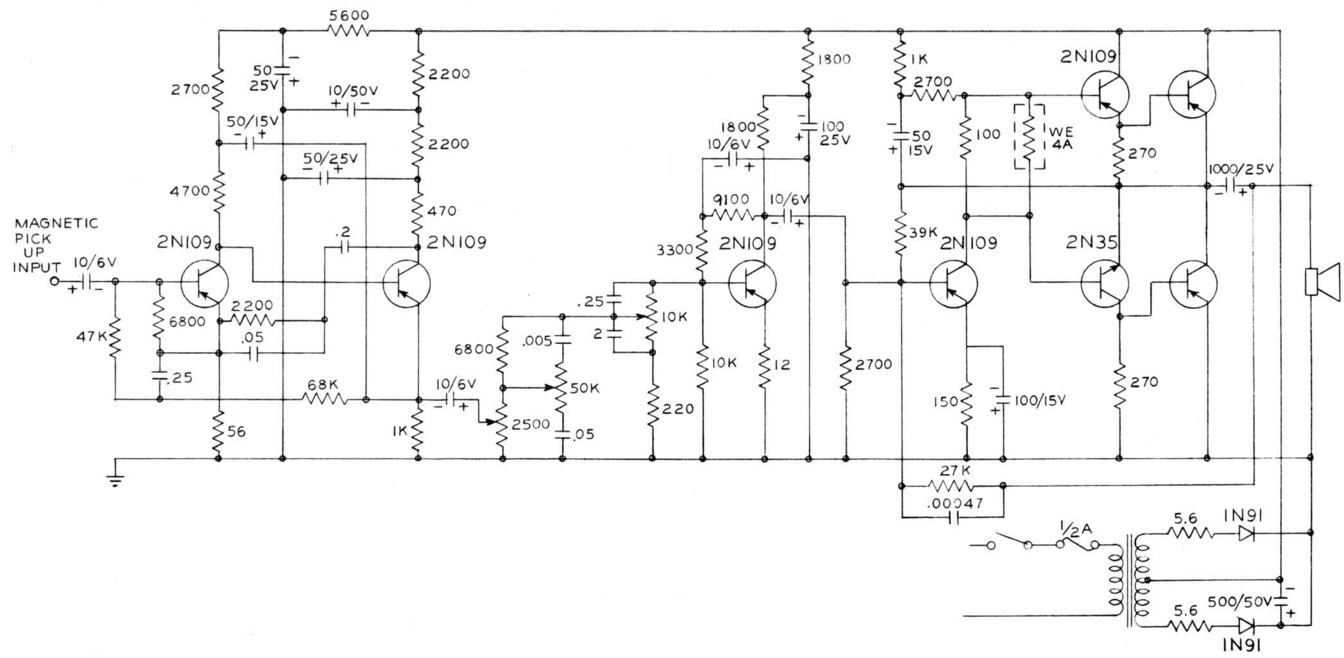

Fig. 12 – Complete phonograph amplifier with variable reluctance pickup input circuit.

is respectively an optimum turns-ratio for the input transformer or an optimum number of turns for the pickup winding. Let V_1 and Z_1 be the V_g and Z_g of either the generator feeding the transformer primary or one turn of the winding on an inductive pickup; and let n be either the turns ratio of the transformer or the number of turns on the inductive pickup. Then

$$\left(\frac{S}{N}\right)_i = \frac{n V_1}{(n^2 Z_1 + r_{bb'})\ \overline{(i_{b'e}^{\,2})}^{1/2}} \qquad (6)$$

The optimum n is that which makes $n^2 Z_1$ equal in magnitude to $r_{bb'}$. For wide band operation where V_1 and Z_1 may vary by many orders of magnitude, the optimum value of n should be chosen to yield the best integrated signal-to-noise ratio. Since the output signal currents of an amplifier at different frequencies are usually the same, the integrated maximum signal-to-noise ratio is obtained when the integrated noise-to-signal ratio,

$$\overline{(N/S)_i^{\,2}} = \frac{\int_{f_1}^{f_2} n_i^2\, df}{S_i^{\,2}} = \int_{f_1}^{f_2} (N/S)_i^{\,2}\, df, \qquad (7)$$

is minimum, where f_1 and f_2 are the lower and upper limits of the amplifier, N_1 is the spot noise output current and S_i is the signal output current at mid-frequencies. The optimum n can be obtained by solving $d\,\overline{(N/S)_i^{\,2}}/dn = 0$.

Although the voltage and impedance of commonly-used pickups need not be optimized to obtain a satisfactory signal-to-noise ratio, the discussion presented may be of interest to those who are interested in low-level signal sources such as tape or microphone input circuits. Actually in the low-noise circuits of Figs. 5, 7, 9, and 10 where the pickup impedance is much less than the input impedance but much greater than the sum of the circuit impedances in series with the base or the emitter for most of the audio frequency range, an increase in n increases the generated voltage but decreases the signal-to-noise ratio. Thus the choice of n is a compromise between greater output current and better signal-to-noise ratio.

H.C. Lin

Derivation of Signal-to-Noise Current Ratio

The hybrid-π equivalent circuit of a base-input transistor stage is shown in Fig. 13. The noise current generator is indicated by $(\overline{i_{b'e}^2})^{1/2}$. The currents due to the signal generator V_g are indicated by solid arrows; while those due to $(\overline{i_{b'e}^2})^{1/2}$ by dotted arrows. For the signal generator, the loop equations are

$$V_g = i_1 r_{b'e} + i_1 (Z_B + Z_g) + i_2 Z_E$$

$$S_i = i_2 - i_1$$

$$V_{b'e} = i_1 r_{b'e} \qquad \text{(i)}$$

$$S_i = g_m V_{b'e}$$

$$\beta = g_m r_{b'e}$$

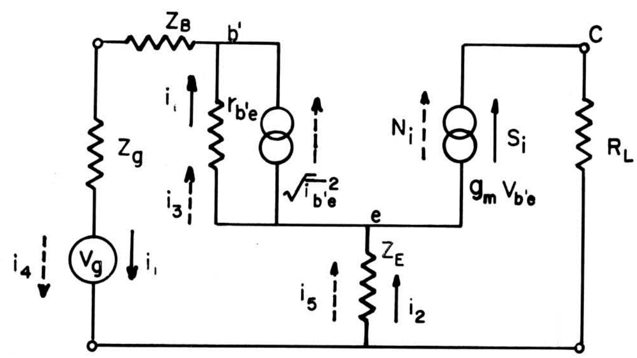

Fig. 13 – Hybrid-π equivalent circuit of a base-input amplifier.

From Eqs. (i), the output signal current is

$$S_i = \frac{\beta V_g}{r_{b'e} + (Z_B + Z_g) + \beta Z_E + Z_E} \qquad \text{(ii)}$$

For the noise generator, the loop equations are

$$i_5 Z_E + i_3 r_{b'e} + i_4 (Z_B + Z_g) = 0$$

$$(\overline{i_{b'e}^2})^{1/2} = i_4 - i_3$$

$$i_5 = N_i + i_3 + (\overline{i_{b'e}^2})^{1/2} \qquad \text{(iii)}$$

$$V^*_{b'e} = i_3 r_{b'e}$$

$$N_i = g_m V^*_{b'e}$$

$$\beta = g_m r_{b'e}$$

From Eqs. (iii), the output noise current is

$$N_i = \frac{\beta (Z_B + Z_g + Z_E)(\overline{i_{b'e}^2})^{1/2}}{r_{b'e} + (Z_B + Z_g) + \beta Z_E + Z_E} \qquad \text{(iv)}$$

Combining Eqs. (ii) and (iv)

$$\frac{S_i}{N_i} = \frac{V_g}{(Z_g + Z_B + Z_E)(\overline{i_{b'e}^2})^{1/2}} \qquad \text{(v)}$$

For the emitter input stage, the equivalent circuit is shown in Fig. 14. The loop equation for the voltage is

$$V_g = i_1 r_{b'e} + i_1 Z_B + i_2 (Z_E + Z_g) \qquad \text{(vi)}$$

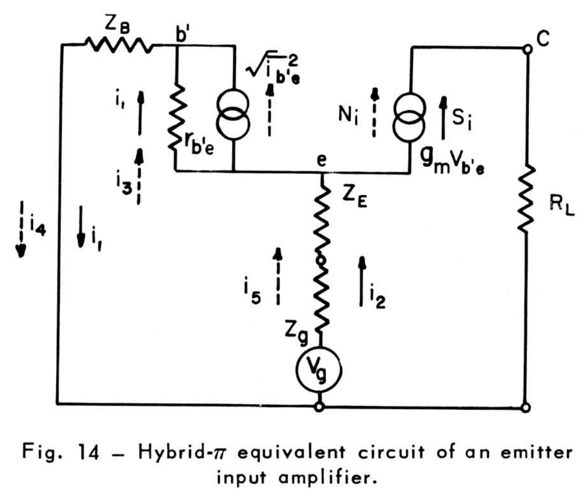

Fig. 14 – Hybrid-π equivalent circuit of an emitter input amplifier.

The only difference between Eq. (vi) and Eq. (i) is that Z_g can now be considered as an addition to Z_E whereas in Eq. (i) Z_g can be considered as an addition to Z_B. Thus for the emitter input connection, it can be deduced from Eq. (ii) that

$$S_i = \frac{\beta V_g}{r_{b'e} + Z_B + \beta(Z_g + Z_E) + (Z_g + Z_e)} \qquad \text{(vii)}$$

Similarly for the noise generator, by adding Z_g to Z_E instead of Z_B in the derivation

$$N_i = \frac{\beta(Z_B + Z_g + Z_E)\left(\overline{i_{b'e}^{\,2}}\right)^{1/2}}{r_{b'e} + Z_B + \beta(Z_E + Z_g) + (Z_g + Z_E)} \qquad \text{(viii)}$$

Combining Eqs. (vii) and (viii),

$$\frac{S_i}{N_i} = \frac{V_g}{(Z_g + Z_B + Z_E)\left(\overline{i_{b'e}^{\,2}}\right)^{1/2}} \qquad \text{(ix)}$$

Note that Eqs. (ix) and (v) are identical.