Vol. 23 FEBRUARY, 1958 No. 2

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SIMPLE METHODS OF MEASURING TRANSISTOR IMPEDANCES

By nature the transistor has the configuration of an active network. In the equivalent network, the impedances differ markedly in magnitude from comparable vacuum-tube impedances. Furthermore, certain of the transistor impedances have no counterpart in the tube.

A knowledge of the magnitude of each transistor impedance aids in the efficient transistorization of circuits. While the average values of these parameters and their spreads are obtainable from some manufacturers' literature, exact values for an individual transistor often are required and must be measured by the user.

Transistor test sets are offered by several instrument manufacturers. However, these complete instruments ordinarily are to be found only in laboratories doing the large amount of transistor work which would justify their cost. In all other instances, the circuit designer is expected to measure transistor impedances with conventional test equipment. This article discusses some of the methods which may be used.

Resistive Parameters

At low audio frequencies, the principal transistor parameters closely approximate the d-c resistive values. Sometimes, it is more convenient and always it is simplier to measure these d-c values.

When the equivalent circuit of the transistor is considered as a T-network (Figure 1), input, output, and transfer resistances are determined in terms of internal base resistance (r_b), collector resistance (r_c), and emitter resistance (r_e). To understand the methods of measurement, it is necessary to see how these internal resistances, or low-frequency impedances, in combination affect the magnitude of the input, output, and transfer resistances.

Since different pairs of transistor electrodes are used for input and output in common-base, common-emitter, and common-collector circuits, it is readily apparent that different internal resistances will be involved in the determination of the parameters. In highly-simplified form, **input resistance** (R_{11}) is equal approximately to $r_e + r_b$ in the common-base and common-emitter circuits, and $r_b + r_c$ for the common-collector. **Output resistance** (R_{22}) is approximately $r_b + r_c$ in the common-base; $r_e + r_c$ in the common-emitter and common-collector. **Forward transfer resistance** (R_{21})

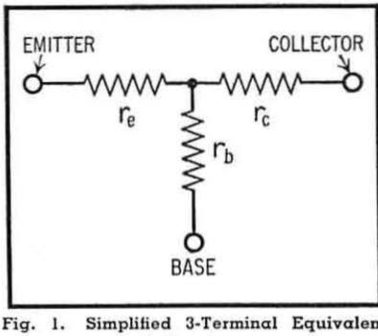

Fig. 1. Simplified 3-Terminal Equivalent of Transistor.

is approximately $r_b + r_m$ for the common-base (where $r_m = ar_c$, a being the emitter-to-collector current amplification factor), $r_c - r_m$ for the common-emitter, and r_c (1–a) for the common-collector. **Reverse transfer** (or **feedback**) **resistance** (R_{12}) is approximately r_b for the common-base,

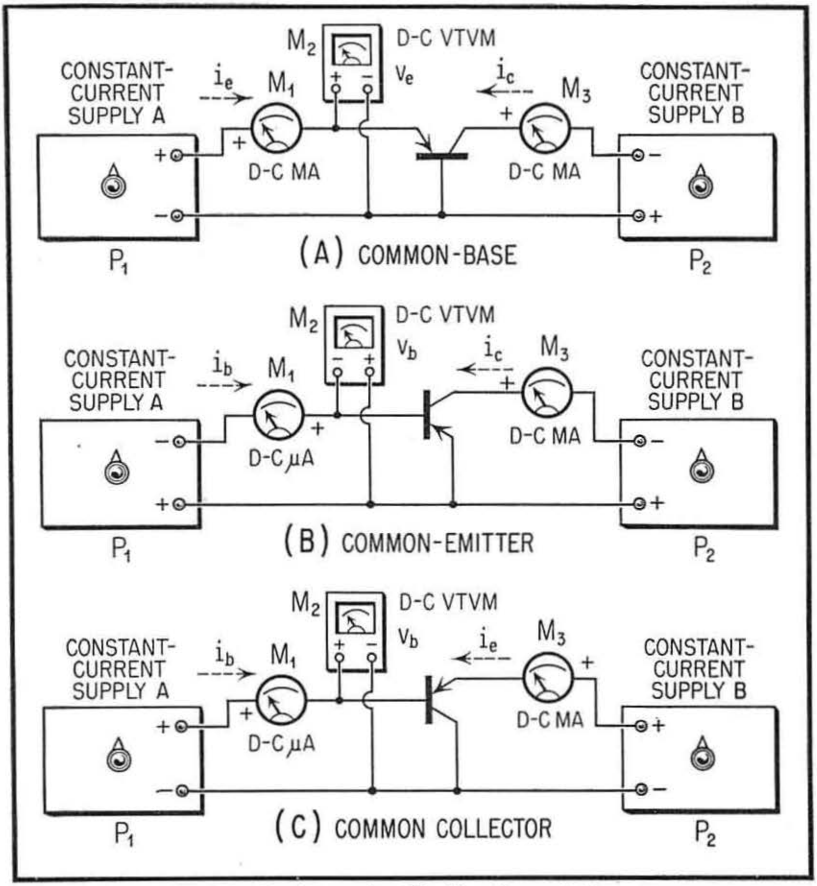

Fig. 2. Setups for Checking R_{11} and R_{12}.

r_e for the common-emitter, and r_c for the common-collector. Exact formulas may be obtained from transistor theory textbooks.

Measurement of Resistive Parameters

The resistive impedances may be measured with simple combinations of d-c vacuum-tube voltmeters, milliammeters or microammeters, and adjustable constant-current d-c supplies. In the following examples, the polarities shown are correct for PNP transistors. When checking NPN transistors, reverse the polarities of all meters and power supplies.

Input Resistance R_{11}. The test circuits are shown in Figure 2. In the common-base circuit (Figure 2A), emitter current i_e is varied while holding collector current i_c constant. The resulting emitter voltage v_e is indicated by the vtvm. A curve of v_e vs. i_e is plotted.

The slope of this curve is R_{11}. A family of curves may be plotted for various constant values of i_e.

In the common-emitter circuit (Figure 2B) and common-collector (Figure 2C), base current i_b is varied while holding collector current i_c constant. The resulting base voltage v_b is indicated by the vtvm. A curve of v_b vs. i_b is plotted. The slope of this curve is R_{11}. A family of curves may be plotted for various constant values of i_c.

Output Resistance R_{22}. The test circuits are shown in Figure 3. In the common-base circuit (Figure 3A), collector current i_c is varied while holding emitter current i_e constant. The resulting collector voltage v_c is indicated by the vtvm. A curve of v_c vs. i_c is plotted. The slope of this curve is R_{22}. A family of curves may

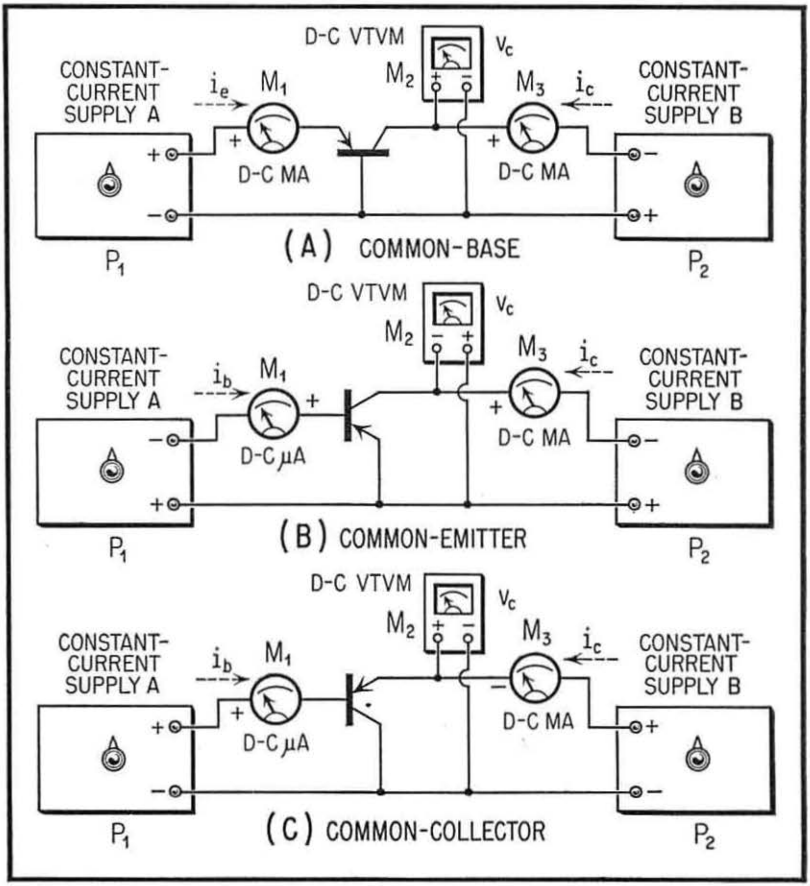

Fig. 3. Setups for Checking R_{21} and R_{22}.

be plotted for various constant values of i_e.

In the common-emitter (Figure 3B) and common-collector (Figure 3C), collector current i_c is varied while holding base current i_b constant. The resulting collector voltage v_c is indicated by the vtvm. A curve of v_c vs. i_c is plotted. The slope of this curve is R_{22}. A family of curves may be plotted for various constant values of i_b.

Reverse Transfer (Feedback) Resistance R_{12}. The test circuits are shown in Figure 1. In the common-base circuit (Figure 1A), collector current i_c is varied while holding emitter current i_e constant. The resulting emitter voltage v_e is indicated by the vtvm. A curve of i_c vs. v_e is plotted. The slope of this curve is R_{12}. A family of curves may be plotted for various constant values of i_e.

In the common-emitter (Figure 1B) and common-collector (Figure 1C), collector current i_c is varied while holding base current i_b constant. The resulting base voltage v_b is indicated by the vtvm. A curve of i_c vs. v_b is plotted. The slope of this curve is R_{12}. A family of curves may be plotted for various constant values of i_b.

Forward Transfer Resistance R_{21}. The test circuits are shown in Figure 3. In the common-base circuit (Figure 3A), emitter current i_e is varied while holding collector current i_c constant. The resulting collector voltage v_c is indicated by the vtvm. A curve of v_c vs. i_e is plotted. The slope of this curve is R_{21}. A family of curves may be plotted for various constant values of i_c.

In the common-emitter (Figure 3B) and common-collector (Figure 3C), base current i_b is varied while holding collector current i_c constant. The resulting collector voltage v_c is indicated by the vtvm. A curve of v_c vs. i_b is plotted. The slope of this curve is R_{21}. A family of curves may be plotted for various constant values of i_c.

Relationships between Parameters. For

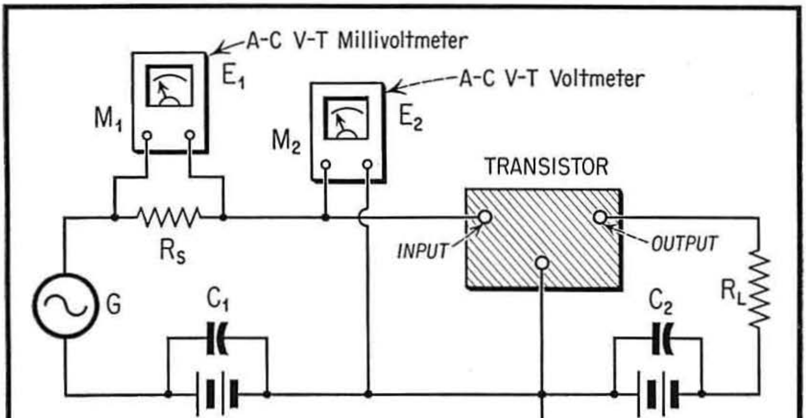

Fig. 4. Circuit for Input Impedance Measurement.

the common-base configuration, $R_{12}=r_b$; therefore, $r_e=R_{11}-R_{12}$. Also, $R_{21}=r_b+r_m$, and $r_m=ar_c$. Alpha (a) is the slope of the curve i_c vs. i_e for constant v_c. For the common-emitter configuration, $R_{12}=r_e$; therefore, $r_b=R_{11}-R_{12}$. Here, $R_{21}=r_e-r_m$, and beta (B) is the slope of the curve i_c vs. i_b for constant v_c. For the common-collector configuration, $R_{12}=r_c$; therefore, $r_e=R_{22}-R_{12}$. Also, $R_{21}=r_c(1\text{-}a)$. Here, beta (B) is the slope of the curve i_e vs. i_b for constant v_e.

Basic A-C Measurements

The resistance values obtained by d-c measurements in the manner just described will be approximately correct for impedances at low audio frequencies. However, the input and output impedances and amplification factor undergo significant changes at higher frequencies. In the common-collector circuit, for example, when the load resistance is constant, R_{11} often shows a reduction of 90 percent between 100 cycles and 50 kc with conventional audio-type transistors, and voltage amplification may undergo an 8 per cent decrease between 10 and 50 kc.

Frequency-sensitive parameters other than the internal resistances of the transistor include alpha, beta, and collector capacitance. In one high-frequency transistor, power gain decreases from its low-frequency value (45 db at 1.5 Mc) to unity at 132 Mc.

When a transistor is to be employed at high frequencies, its input and output impedances, which are extremely important in circuit design, should be measured under a-c conditions, preferably at the actual frequency of operation.

Figure 4 illustrates one method of determining transistor input impedance (Z_i) in terms of alternating voltage and current. The configuration may be either common-base, common-emitter, or common-collector as required, hence the transistor is shown here as a block with three terminals. Batteries B_1 and B_2 represent the d-c bias voltages required by the input and output electrodes, respectively, to set the transistor operating point. A low-impedance generator, G, supplies a test-signal voltage at the operating frequency and this voltage alternates between peak values slightly higher and lower than the d-c voltage of B_1. Thus, the input signal to the transistor fluctuates over a small increment. Usually, this generator is an a-f or r-f signal generator having low output impedance. High capacitances, C_1 and C_2, bypass the d-c sources at the generator frequency. The a-c input voltage (E_2) is indicated by a high-impedance vtvm, M_2. An a-c vacuum-tube millivoltmeter, M_1, is shunted by resistance R_s which is much lower than the input impedance of any transistor to be tested. Its deflection therefore is proportional to the a-c signal-input current. Thus, meter M_1 effectively is an a-c milliammeter. The a-c input current is equal to E_1/R_s, where E_1 is the deflection of meter M_1.

The transistor is terminated in the normal load impedance, R_L, into which it is to operate in the circuit to which it will be applied. This is a necessary condition, since input impedance is sensitive to load impedance.

Since $Z=E/I$, the input impedance Z_i of the transistor is calculated from the deflections of M_1 and M_2. Thus, $Z_i=E_2/(E_1/R_s) = (E_2R_s)/E_1$; where R_s and Z_i are in ohms, and E_1 and E_2 in volts.

Figure 5 illustrates a similar 2-meter method of determining transistor output impedance (Z_o). As in the preceding example, batteries B_1 and B_2 represent the d-c bias voltages required by the input and output electrodes,

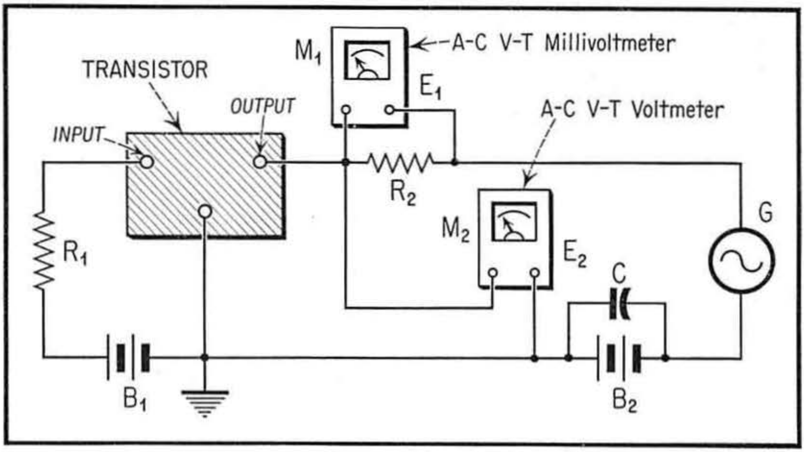

Fig. 5. Circuit for Output Impedance Measurement.

respectively, for the desired operating point of the transistor. The low-impedance generator, G, supplies a test-signal voltage which alternates between peak values slightly higher and lower than the d-c voltage of B_2. Thus, the test signal applied to the output electrodes of the transistor fluctuates over a small increment. Resistor R_1 provides an input impedance path equal to the impedance out of which the transistor will operate in the circuit to which it will be applied. High capacitance C bypasses d-c source B_2 at the operating frequency. The a-c test voltage (E_2) is indicated by a high-impedance a-c vtvm, M_2. An a-c vacuum-tube millivoltmeter, M_1, is shunted by resistance R_2 which is much lower than the output impedance of any transistor to be tested. Its deflection therefore is proportional to the test-signal current. As in the preceding example, meter M_1 effectively is an a-c milliammeter. The a-c test-signal current is equal to E_1/R_2.

Using Ohm's Law, output impedance is calculated from the deflections of M_1 and M_2: $Z_o = E_2/(E_1/R_2) = (E_2R_2)/E_1$; where R_2 and Z_o are in ohms, and E_1 and E_2 in volts.

It should be noted that considerable care is required for successful measurements using the schemes illustrated by Figures 4 and 5, especially at radio frequencies. To begin with, meter M_1 in each instance is operated above ground, hence it should be of the self-contained battery type to avoid power line complications. All leads in the test circuit must be as short as practicable, but stray capacitances and interaction due to close spacing of instruments must be avoided. The shunt resistor (R_s in Figure 4; R_2 in Figure 5) must be non-inductive. The load (R_L in Figure 4) and the equivalent driving impedance (R_1, Figure 5) must be the identical impedance devices which will be used in the final circuit, although they are represented here as simple resistances. The d-c electrode bias currents must be set exactly to the desired levels (by adjustment of B_1 and B_2) to maintain the transistor at the desired operating point. A d-c milliammeter or microammeter, inserted temporarily in series with B_1 and then B_2, may be used for this purpose.

Use of Bridge

The resistive and reactive components of transistor input and output impedances may be evaluated separately by conventional a-c bridge methods. The input or output circuit of the transistor constitutes the unknown arm of the bridge.

For this purpose, the transistor must be dc-biased in a manner somewhat similar to the application of a polarizing d-c voltage to an electrolytic capacitor or iron-core choke during bridge measurements. The bias currents must be measured accurately with suitable d-c milliammeters or microammeters and set to the desired operating level. Both the input and output electrodes of the transistor should be dc-biased during the measurement. Suitable choke coils or isolating resistors must be employed to block the flow of the a-c bridge currents into the bias supplies. The bridge signal must be held low enough to prevent exceeding either the normal operating voltage or peak inverse voltage ratings of the transistor.

Amplifier Impedances

Figure 6 shows a simple setup for checking the input impedance (Z_i) of a transistorized amplifier. In this arrangement, the amplifier is terminated in its normal load impedance, R_L. The latter may be the actual load device, such as a loudspeaker, or may be an equivalent resistance.

The test signal is supplied by a suitable signal generator or test oscillator. A calibrated, non-inductive, variable resistor (R) is connected in series with the generator and the amplifier input terminals. An a-c vtvm is arranged with a spdt switch (S) to read signal voltage e_1 before the resistor (Position a) or e_2 after the resistor (Position b).

In operation, switch S first is thrown to a and voltage e_1 observed. The switch then is thrown to b, and resistor R is adjusted carefully to set e_2 equal exactly to $\frac{1}{2}e_1$. At this point, the resistance setting of R equals

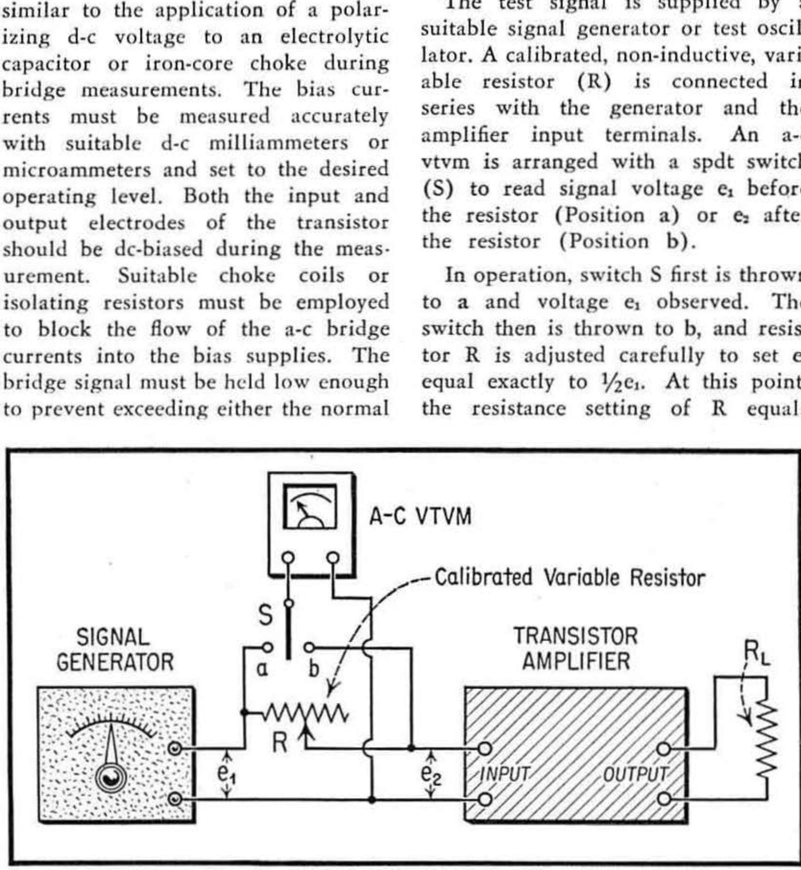

Fig. 6. Checking Transistor Amplifier Z_i.

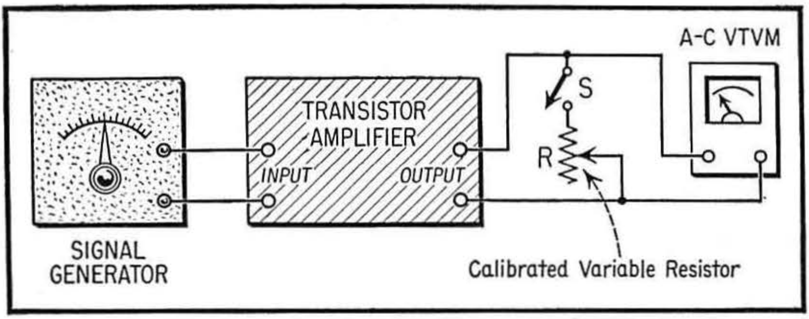

Fig. 7. Checking Transistor Amplifier Z_o.

the input impedance of the amplifier and may be read directly from the resistor calibration. If the resistor is not direct-calibrated, it may be removed from the circuit and its resistance setting measured with an ohmmeter or bridge. Throughout the measurement, the test voltage must be held to an amplitude low enough to prevent overdriving of the amplifier The test may be repeated at a number of frequencies to determine the variation of Z_i with frequency.

Figure 7 shows a similar circuit for measuring the output impedance (Z_o) of a transistorized amplifier. In this arrangement, the signal generator or test oscillator supplies a signal voltage to the input of the amplifier. The amplitude of this voltage must be restricted to prevent overdriving the amplifier. A calibrated, non-inductive, variable resistor (R) is connected to the amplifier output terminals through a spst switch (S). An a-c vtvm indicates the amplifier output voltage.

The output voltage (e_1) is read with switch S open. The switch then is closed and resistor R adjusted to set the voltage to a new level e_2 equal exactly to $\frac{1}{2}e_1$. At this point, the resistance setting of R equals the output impedance of the amplifier which may be read directly from the resistor calibration. If an uncalibrated resistor is employed, it may be removed from the circuit and its resistance setting checked with an ohmmeter or bridge.

When checking an amplifier employing a power-transistor output stage, resistor R must be rated to dissipate safely at least twice the expected power output of the amplifier.

Additional, detailed data on transistor impedance measurements may be found in the following sources.

1. **Principles of Transistor Circuits.** Richard F. Shea, Editor. (John Wiley & Sons, Inc.; New York, N. Y.). pp. 485-503.

2. **Transistors, Theory & Practice.** Rufus P. Turner. (Gernsback Library, Inc.; New York, N. Y.). pp. 109-121.

3. **Transistor Characteristics at Low and Medium Frequencies.** L. J. Giacoletto. TELE-TECH & ELECTRONIC INDUSTRIES, March 1953. p. 97.

4. **Surface-Barrier Tranistor Measurements and Applications.** Roland J. Turner. TELE-TECH & ELECTRONIC INDUSTRIES, August 1954. p. 79.