Service Scope

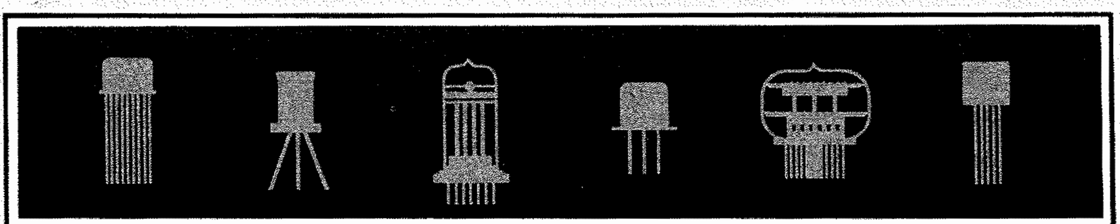
USEFUL INFORMATION FOR USERS OF TEKTRONIX INSTRUMENTS

NUMBER 43 PRINTED IN U.S.A. APRIL 1967

PRACTICAL APPROACH TO TRANSISTOR AND VACUUM TUBE AMPLIFIERS

BY F. J. BECKETT
TEKTRONIX, INC.
ELECTRONIC INSTRUMENTATION GROUP
DISPLAY DEVICES DEVELOPMENT

PART 2
THE VACUUM TUBE AMPLIFIER



This is the second in a series of three articles offering a new approach to transistor and vacuum-tube amplifiers. This new approach is based on a simple DC analysis that incorporates the concepts of "transresistance" and the principles of Thévenin's Theorem.

Part 1, "The Transistor Amplifier", which appeared in the February, 1967 issue of SERVICE SCOPE considered the transistor amplifier as a simple DC model. This second article looks at the vacuum-tube amplifier in a similar light and sees some striking similarities in the two devices.

X-2344

In the previous article (Part I, "The Transistor Amplifier) of this series, it was shown that the gain of a linear transistor amplifier is set by external conditions. The same reasoning can also be applied to vacuum tubes. The equivalent circuit of a vacuum-tube amplifier is shown in Figure 9. The current that is produced in the plate circuit by the signal (E_g) acting on the grid is taken into account by postulating that the plate circuit can be replaced by a generator, $-\mu E_g$ having an internal resistance (rp). We may also consider a vacuum-tube amplifier in terms of the constant-current form by replacing the voltage generator in the constant-voltage form with a current generator (gm E_g) shunting the internal resistance (rp).

These two approaches are valid in every respect but they do not convey much to us in the practical sense. Let us now consider a vacuum-tube amplifier from another approach.

In an amplifier which has its grid referenced to ground all plate-circuit impedances, R_L and rp, when viewed from the cathode are multiplied by the term $\frac{1}{\mu + 1}$. Also, by the same reasoning, the cathode impedances when viewed from the plate circuit are multiplied by the term $(\mu + 1)$. Therefore, the impedance we see looking into the cathode must be $\frac{rp + R_L}{\mu + 1}$, where μ equals the amplification factor of the tube.

Hence it is reasonable to suppose that the voltage E_c, reference Figure 10, appears across this impedance we see looking into the cathode.

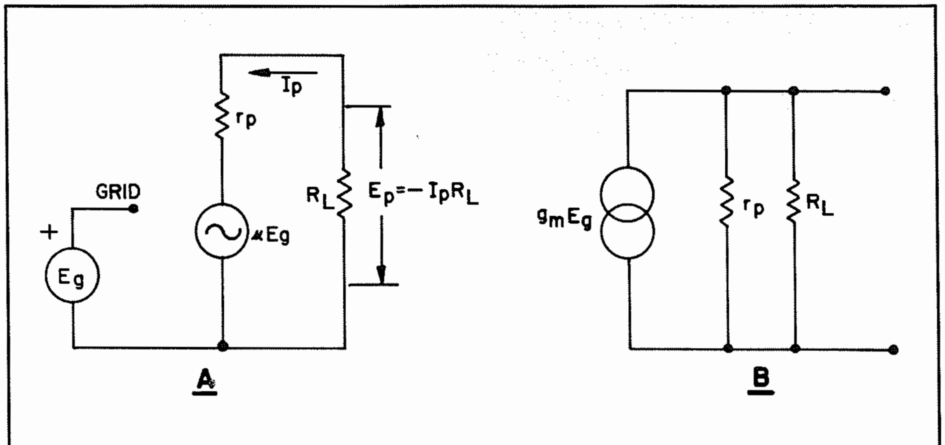


Figure 9. Illustrating the more familiar equivalent circuit of a vacuum tube amplifier.
(a) The constant voltage generator form or the Thévenin equivalent.
(b) The constant current generator form or the Norton equivalent.

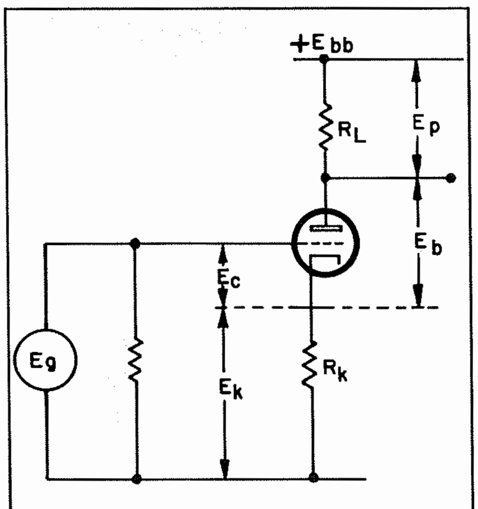


Figure 10. A vacuum tube amplifier in the grounded cathode configuration showing the various voltage measurements around the circuit.

The Triode Amplifier (Ground Cathode)

We will now look at a triode amplifier in terms related to our equivalent circuit. The common component is of course, the plate current. The change in this current due to the action of a control grid will determine the output voltage across the load impedance (R_L).

Now $E_g = E_c + E_k$ (19)

That is to say

$$E_g = I_p \left[\frac{rp + R_L}{\mu + 1}\right] + I_p R_k$$

$$\text{Or, } E_g = I_p \left[\left(\frac{rp + R_L}{\mu + 1}\right) + R_k\right] \quad (20)$$

Also, $E_{bb} = E_b + E_p + E_k$ (21)

or $E_b = E_{bb} - E_p - E_k$ (22)

and $E_p = -I_p R_L$ (23)

We define the voltage gain $A_{(v)}$ as

$$A_{(v)} = \frac{E_p}{E_g} \quad (24)$$

$$\text{Then } A_{(v)} = -\frac{I_p R_L}{I_p \left[\left(\frac{rp + R_L}{\mu + 1}\right) + R_k\right]}$$

$$= -\frac{R_L}{\left(\frac{rp + R_L}{\mu + 1}\right) + R_k} \quad (25)$$

We now have arrived at an equation for gain which is a ratio of impedances. The same approach may be applied to the grounded-grid configuration and we arrive at a similar result, except the sign is positive.

The Pentode Amplifier

In the triode amplifier all the cathode current will flow through the output load impedance (R_L). However, in the case of the pentode and other multigrid tubes, some of this current is diverted into the screen. Equation (23) defines the output voltage in terms of the plate current. Therefore, to derive the actual gain figure we must determine the actual amount of cathode current which will finally reach the plate and become signal current. This figure can be arrived at from a graphical analysis of the mutual-conductance curves. In most cases, about 72% of the cathode current reaches the plate to become signal current. A typical example is a type 12BY7 pentode. However, this figure can be as high as 90% for some types—for example a 7788 pentode. The ratio of the plate current (I_p) to the cathode current (I_k) is the plate efficiency factor, i.e., $\eta = \frac{I_p}{I_k}$.

Now let is reexamine what effect this fact must have on the gain of a pentode amplifier as compared to a triode amplifier. The impedance we see looking into the cathode of a pentode is the same as for a triode.

That is $\frac{rp + R_L}{\mu + 1}$

however rp >> R_L and therefore R_L can usually be neglected in this equation.

That is to say $\frac{rp}{\mu + 1} \approx \frac{1}{gm}$

and since conductance is the reciprocal of resistance we will call this impedance r_k.

$$\text{i.e. } r_k = \frac{1}{gm} \quad (26)$$

We have seen that the gain equation of the triode amplifier is defined in terms of the parameters μ and rp. We should not lose sight of the fact that μ and rp are related to the plate current and therefore when these parameters are transferred to cathode dimensions these terms must be multiplied by the plate efficiency factor (η). That is to say the impedance we see looking into the cathode r_k must be multiplied by (η). With these facts in mind let us now derive the gain equation for a pentode amplifier.

We recall that:

$$E_b = E_{bb} - E_p - E_k \quad (22)$$

$$\text{and } E_p = -I_p R_L \quad (23)$$

$$\text{also } E_g = E_c + E_k \quad (19)$$

$$= \eta r_k I_k + I_k R_k \quad (27)$$

$$\text{but } I_k = \frac{I_p}{\eta} \quad (28)$$

Therefore substituting equation (28) in equation (27)

$$E_g = \frac{\eta r_k I_p}{\eta} + \frac{I_p R_k}{\eta}$$

$$= I_p \left(r_k + \frac{R_k}{\eta}\right) \quad (29)$$

and since the voltage gain

$$A_{(v)} = \frac{E_p}{E_g}$$

$$= -\frac{I_p R_L}{I_p \left(r_k + \frac{R_k}{\eta}\right)}$$

$$= -\frac{R_L}{r_k + \frac{R_k}{\eta}} \quad (30)$$

The same remarks we made about the external emitter resistor R_E (refer to Part No. 1, The Transistor Amplifier) apply equally as well to the cathode resistor, R_k; *namely, R_k will be that impedance in which the signal current will flow to the AC ground.*

In the case of the grounded plate (the cathode follower) we do not need to consider the plate efficiency factor if the amplifier is triode connected, therefore, the "gain" can be considered in terms of a simple divider network which can never be greater than unity.

$$A_{(v)} = \frac{R_k}{R_k + r_k} \quad (31)$$

The Push-Pull Amplifier

We can view a push-pull amplifier in a similar light by recognizing the existence of a virtual AC ground point between the cathodes of $V_{(1)}$ and $V_{(2)}$ as shown in Figure 11. Therefore, the gain of a push-pull triode amplifier will be:

$$A_{(v)} = \frac{R_{L(1)} + R_{L(2)}}{r_{k(1)} + r_{k(2)} + R_{k(1)} + R_{k(2)}} \quad (32)$$

where subscripts (1) and (2) are associated with $V_{(1)}$ and $V_{(2)}$.

And if:

$$R_{k(1)} = R_{k(2)}$$

$$\text{and } r_{k(1)} = r_{k(2)}$$

which is usually the case; then,

$$A_{(v)} = \frac{R_{L(1)} + R_{L(2)}}{2r_k + 2R_k} \quad (33)$$

$$\text{Where } r_k = \frac{r_p + R_L}{\mu + 1} \text{ (either } V_{(1)} \text{ or } V_{(2)})$$

$$\text{and } R_k = R_{k(1)} \text{ or } R_{k(2)}$$

With a push-pull pentode amplifier we must consider the plate-efficiency factor (η). Therefore,

$$A_{(v)} \text{ pentode} = \frac{R_{L(1)} + R_{L(2)}}{2r_k + \frac{2R_k}{\eta}} \quad (34)$$

$$\text{where } r_k = \frac{1}{gm} \text{ either } V_{(1)} \text{ or } V_{(2)}$$

$$R_k = R_{k(1)} \text{ or } R_{k(2)}$$

η = plate-efficiency factor of either $V_{(1)}$ or $V_{(2)}$.

The Cascode Amplifier

The cascode amplifier fundamentally consists of two tubes connected in series, see Figure 12. Normally we usually fix the grid of $V_{(1)}$ at some positive voltage.

The key to understanding this type of circuit is to consider $V_{(2)}$ as a voltage-activated current generator. All the current delivered by $V_{(2)}$ passes through the output load impedance R_L. Any change in voltage appearing at the grid of $V_{(2)}$ appears as a change in current across R_L. We can derive the gain equation in the same way as we did for a pentode amplifier. There is no need to consider (η) if both tubes are triodes.

$$A_{(v)} \text{ (stage)} = \frac{R_{L(1)}}{R_{k(2)} + r_{k(2)}} \quad (35)$$

$$\text{where } r_{k(2)} = \frac{r_{p(2)}}{\mu_{(2)} + 1}$$

$$= \frac{1}{gm_{(2)}}$$

where the subscripts (1) and (2) are associated with $V_{(1)}$ and $V_{(2)}$.

One of the advantages of this type of circuit is that the internal impedance which shunts R_L is extremely high.

In this respect the triode cascode amplifier closely approximates a pentode amplifier. If we compare the plate-current versus plate-voltage curves of both devices we see a close resemblance.

The Hybrid Cascode Amplifier

Figure 13 is a typical configuration consisting of a vacuum tube V_1 and a transistor, Q_1, connected in series. We can apply much the same approach as we did for the cascode vacuum-tube amplifier. Let us assume the base to emitter junction of Q_1 to be forward biased. The collector current of Q_1 becomes the plate current of V_1. Therefore, any change occurring at the base of Q_1 is reflected as a change in plate current in V_1.

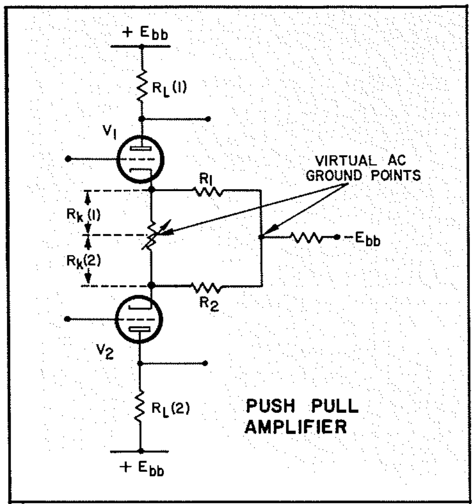


Figure 11. A typical push-pull triode amplifier. We normally encounter two virtual AC ground points between the cathodes V_1 and V_2. It may be necessary to consider the effect of the virtual AC ground point at the junction of R_1 and R_2. If R_1 or R_2 is large in value compared respectively to $R_{k(1)}$ or $R_{k(2)}$ then we can neglect this virtual AC ground and consider R_k in terms of $R_{k(1)}$ or $R_{k(2)}$. However, if this is not so, R_k will be the parallel combination of $R_{k(1)}$ and R_1 or $R_{k(2)}$ and R_2.

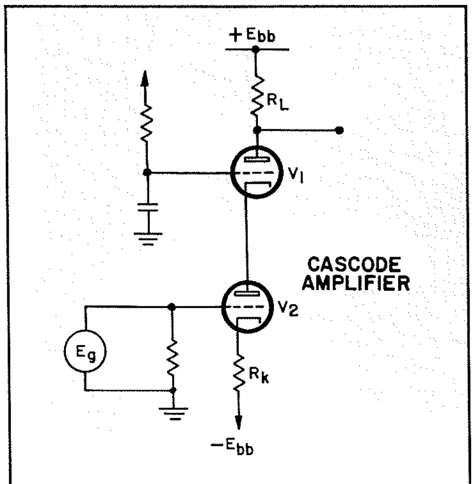


Figure 12. Illustrating a cascode amplifier using two triodes.

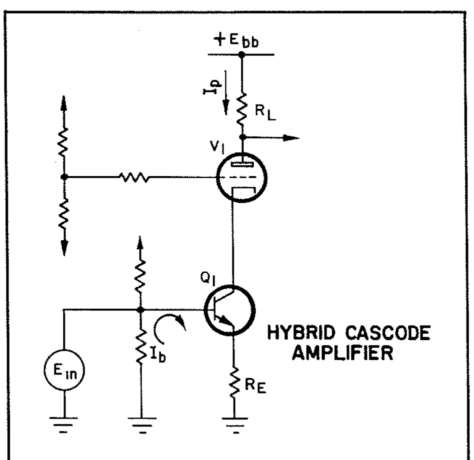
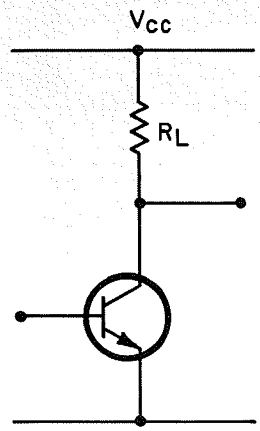
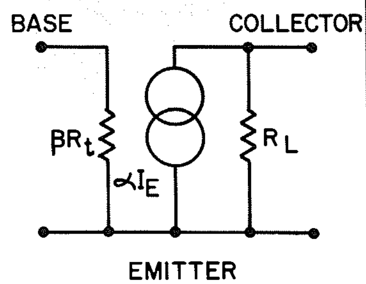


Figure 13. A typical hybrid cascode amplifier using a transistor and a vacuum tube.

BASIC CIRCUIT	EQUIVALENT CIRCUIT	EQUATIONS	REMARKS

COMMON EMITTER





GAIN = $A(v) = -\frac{R_L}{R_t}$

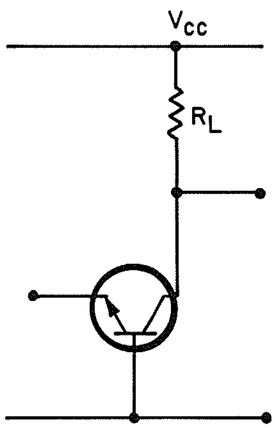
RIN = βR_t

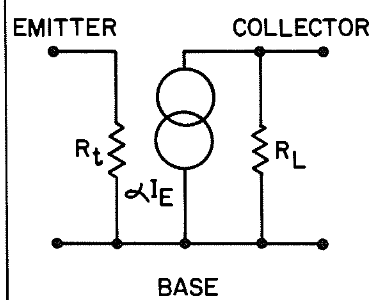
A resistance (R_E) between the emitter terminal of the transistor to the AC ground will modify the gain equation and the input impedance; then,

$A(v) = -\frac{R_L}{R_t + R_E}$ and

$R_{in} = \beta (R_E + R_t)$.

COMMON BASE





GAIN = $A(v) = +\frac{R_L}{R_t}$

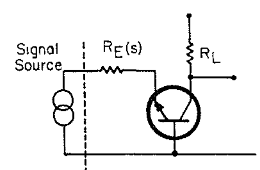
RIN = R_t

ROUT = R_L

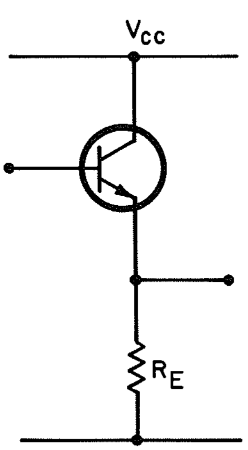
The equivalent resistance $R_E(s)$ between the input signal source and the emitter terminal of the transistor will modify the gain equation and the input impedance as seen from the signal source; then,

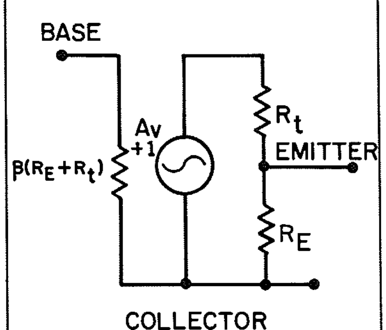
$A(v) = +\frac{R_L}{R_t + R_E(s)}$ and

$R_{in} = R_t + R_E(s)$.



COMMON COLLECTOR





GAIN = $A(v) = \frac{R_E}{R_E + R_t}$

RIN = $\beta (R_E + R_t)$

ROUT = $(R_t + \frac{1}{\beta})$ in parallel with R_E

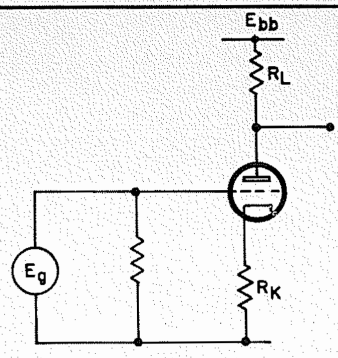
The actual value of R_{out} will depend on what resistance is connected to the base. Let us assume the base is directly coupled to the preceding stage. The equivalent output impedance of the preceding stage becomes the numerator over beta in the second term in the parenthesis and the output impedance of the stage under consideration R_{out} is modified accordingly; eg., if the output impedance of the previous stage is 100 Ω, then

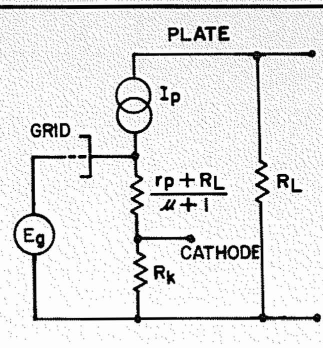
$R_{out} = (R_t + \frac{100}{\beta})$ in parallel with R_E.

Figure 8.

BASIC CIRCUIT (TRIODE)	EQUIVALENT CIRCUIT	EQUATIONS

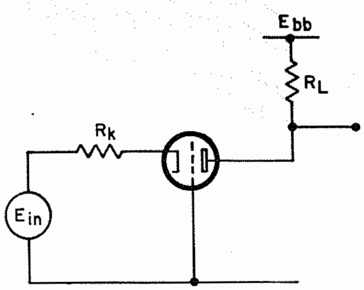
GROUNDED CATHODE

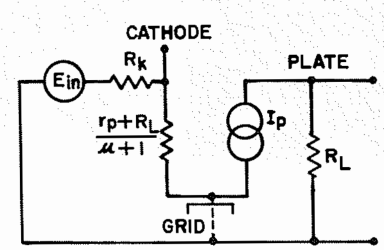




$$GAIN = A_{(v)} = -\frac{R_L}{\frac{r_p + R_L}{\mu + 1} + R_k}$$

GROUNDED GRID

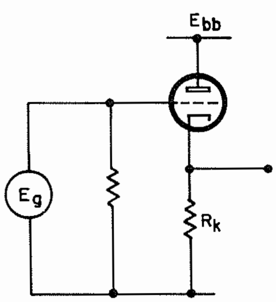


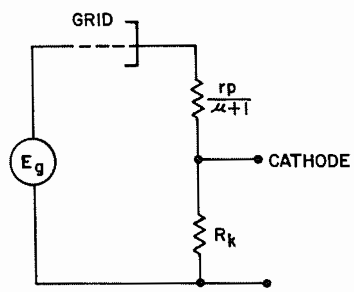


$$GAIN = A_{(v)} = +\frac{R_L}{\frac{r_p + R_L}{\mu + 1} + R_k}$$

$$R_{IN} = R_k + \frac{r_p + R_L}{\mu + 1}$$

GROUNDED PLATE





$$GAIN = A_{(v)} = +\frac{R_k}{R_k + r_k}$$

$R_{OUT} = r_k$ in parallel with R_k

WHERE: $r_k = \frac{r_p}{\mu + 1}$

PENTODE AMPLIFIER

$$GAIN = A_{(v)} = \frac{R_L}{r_k + \frac{R_k}{\eta}}$$

WHERE:

R_L = LOAD RESISTANCE

$r_k = \frac{1}{gm}$

R_k = CATHODE RESISTOR (Refer Text)

η = PLATE EFFICIENCY FACTOR

PUSH PULL AMPLIFIER

TRIODE PAIR

$$GAIN = A_{(v)} = \frac{R_{L(1)} + R_{L(2)}}{2r_k + 2R_k}$$

WHERE:

$$r_k = \frac{r_p + R_L}{\mu + 1}$$

PENTODE PAIR

$$GAIN = A_{(v)} = \frac{R_{L(1)} + R_{L(2)}}{2r_k + \frac{2R_k}{\eta}}$$

WHERE: $r_k = \frac{1}{gm}$

SUBSCRIPTS (1) AND (2) ARE ASSOCIATED WITH V_1 AND V_2

CASCODE AMPLIFIER

$$GAIN = A_{(v)} = \frac{R_{L(1)}}{r_{k(2)} + R_{k(2)}}$$

WHERE:

$$r_k = \frac{1}{gm(2)}$$

HYBRID CASCODE AMPLIFIER

$$GAIN = A_{(v)} = \frac{R_L}{R_E + R_t}$$

WHERE:

R_L = LOAD RESISTANCE

* $R_t = r_e + R_r$

* R_E = EXTERNAL EMITTER RESISTANCE

* REFER PART I "THE TRANSISTOR AMPLIFIER"

Figure 16

We recall (Part 1, The Transistor Amplifier, Eq. 10) that the input impedance we see looking into the base of a transistor in the common-emitter configuration is:

$$R_{in} = \beta (R_E + R_t) \qquad (10)$$

Now $E_{in} = I_b R_{in}$

$$= I_b \, \beta (R_E + R_t) \qquad (36)$$

also $\beta = \frac{I_c}{I_b}$

or $I_c = \beta \, I_b \qquad (37)$

therefore substituting equation (37) in equation (36)

$$E_{in} = I_c (R_E + R_t) \qquad (38)$$

now the collector current Q_1 becomes the plate current of V_1. Then,

$$E_{in} = I_p (R_E + R_t) \text{ since } I_p = I_c \quad (39)$$

also $E_p = -I_p R_L \qquad (23)$

and since

$$A_{(v)} \text{ (stage)} = \frac{E_p}{E_{in}}$$

then from equations (23) and (39)

$$A_{(v)} \text{ (stage)} = -\frac{I_p R_L}{I_p (R_E + R_t)}$$

$$= -\frac{R_L}{R_E + R_t} \qquad (40)$$

If the vacuum tube is not a triode but some other multigrid tube such as a pentode, the gain equation will have to be multiplied by the plate efficiency factor (η).

The same remarks concerning the output impedance of the vacuum-tube cascode amplifier can be applied to the hybrid counterpart.

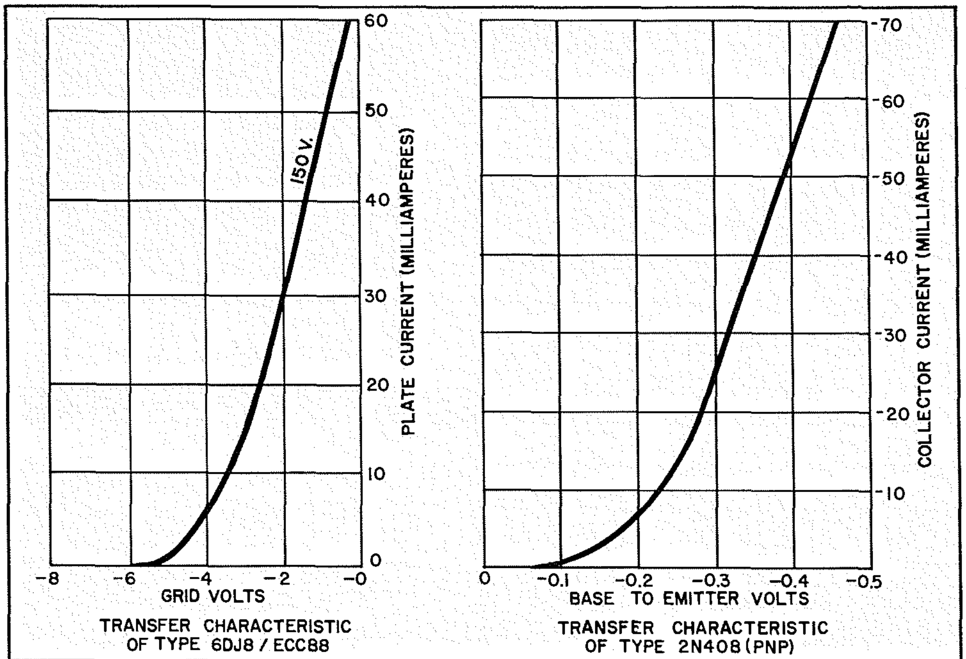


Figure 14. The transfer characteristic curves of a vacuum tube (6DJ8) and a PNP transistor (2N408), illustrating the basic similarity between vacuum tubes and transistors.

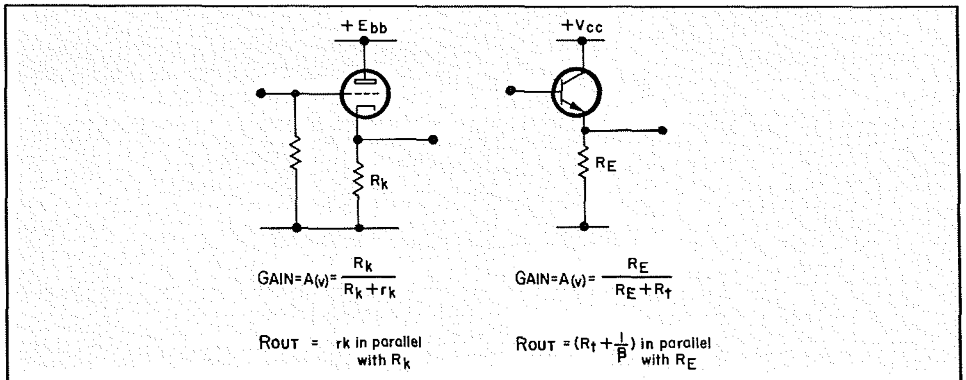


Figure 15. The analogy between the cathode follower (grounded plate) and the emitter follower (the common collector) in terms of "gain" and output impedances of both devices.

Summary

We have shown that the gain of a linear amplifier, transistor or vacuum tube, is a ratio of impedances. We can, of course, derive the gain equations for both devices in terms of mutual conductance. In fact, if we compare the transfer curves of both devices, Figure 14, we see a striking similarity. V_{BE} and E_g can be thought of in the same terms and in like manner I_p and I_c perform identical functions. Our analysis of both devices has shown that this fact is not coincidence.

It is not unreasonable to say that when we compare the cathode-follower (grounded-plate) against the common-collector configuration, Figure 15, we can think of both devices as being identical in operation—differing only in concept. The same argument can be put forward about the common-base amplifier and the grounded-grid amplifier. So too, the common-emitter amplifier and the grounded-cathode amplifier if we chose to ignore the input impedances of both devices.

Figure 16 (see page 5) summarizes the results of our analysis of the grounded cathode, grounded grid, and grounded plate amplifiers. Opposite this Figure we have reprinted Figure No. 8 from the previous article (Part I, The Transistor Amplifier) which summarized the results of the analysis on the three types of transistor amplifiers. These two charts will assist you to follow more closely our analysis of the 545B vertical amplifier (appearing in the next issue of SERVICE SCOPE) and to make a comparison between transistor and vacuum tube amplifiers.

It is not surprising we sometime find ourselves explaining one device in terms of another. Nature has a charming way of making most things interdependent upon one another. Recognize this fact and most tasks become a little easier.

The third and concluding article in this series will appear in the June, 1967 issue of SERVICE SCOPE. That article will present an analysis of a typical Tektronix hybrid circuit—a Type 545B Oscilloscope's vertical amplifier.

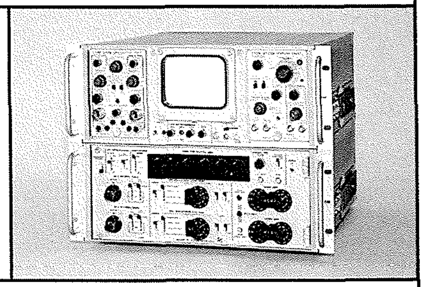
The analysis will be based on conclusions reached in Part 1 (February, 1967 issue) and Part 2 (this issue) of the series of articles.

ERRATA

We call your attention to a typographical error in the caption under Figure 7 in the February issue of SERVICE SCOPE. The Figure referred to in the last line of this caption should be Figure 8—not Figure 7.

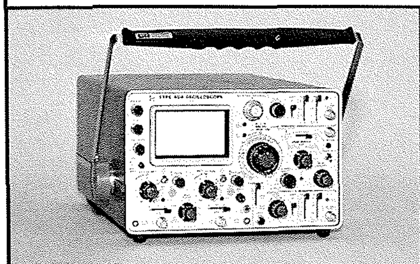
New From Tektronix, Inc. In 1967

For complete information, contact your Field Engineer, Field Representative, or Distributor.



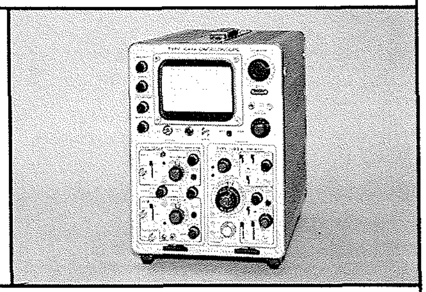
DIGITAL READOUT OSCILLOSCOPE

The Type 568 Readout Oscilloscope accepts sampling and real-time amplifiers and time-base units. Used with the Type 230 Digital Unit, digital readout of measurements (in addition to the analog CRT display) is provided, allowing faster and more accurate answers than using the CRT alone. A wide variety of repetitive pulse measurements can be made digitally, without operator error: pulse voltage, risetime, delay time, storage time, and pulse width, among others. Measurement limits may be selected to provide Go/No-Go indicators.



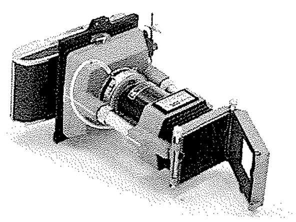
DC-to-150 MHz PORTABLE OSCILLOSCOPE

The Type 454 provides accurate dual-trace displays of fast-rise pulses and high-frequency signals previously beyond the capability of most real-time oscilloscopes. Risetime with included 10X probes is 2.4 ns. Other features include X-Y displays to 5 mV/div, chopped or alternate switching between inputs, calibrated sweep delay, and rugged design for environmental extremes.



DC-to-100 MHz OSCILLOSCOPE

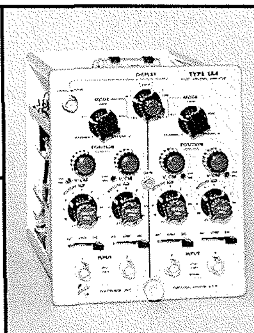
The Type 647A with choice of amplifier and time-base units provides accurate displays over a wide range of temperature and other environmental extremes. Bandwidth and triggering extend to 100 MHz with the new Type 10A2A Dual-Trace Plug-In and Type 11B2A Sweep-Delay Time Base Plug-In. Differential comparator and single time-base plug-ins are also available. The Type 647A has 14-kV accelerating potential for bright 6 x 10-cm displays.

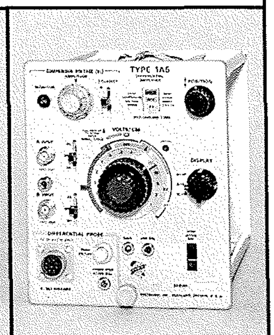


HIGH-SPEED CAMERA

The C-40 is a high-performance camera for Tektronix portable oscilloscopes. The f/1.3—1:0.5 lens and Polaroid* Roll-Film back for 10,000-speed film provide the writing speed necesary to record single-shot events on the Type 454 Oscilloscope.

*Registered Trade-Mark Polaroid Corporation



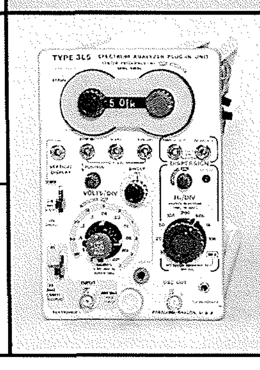


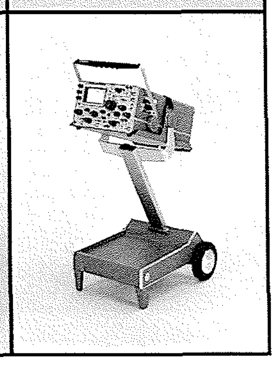
DC-to-50 MHz FOUR-TRACE AMPLIFIER

The Type 1A4 Plug-In Unit for Type 530, 540, 550, and (with adapter) 580-Series Oscilloscopes provides the equivalent of two wide-band, dual-trace units connected to a third wide-band, dual-trace unit. Unique display logic provides unprecedented display flexibility including four-channel adding (± 1 ± 2) + (± 3 ± 4). Deflection factor is 10 mV/cm to 20 V/cm.

DC-to-50 MHz DIFFERENTIAL AMPLIFIER

The Type 1A5 Plug-In Unit for Type 530, 540, 550, and (with adapter) 580-Series Oscilloscopes achieves a new high in common-mode rejection. Gain-bandwidth products exceed those previously available in a differential amplifier. Bandwidths from DC to 50 MHz can be achieved at 5 mV/cm, DC to 45 MHz at 2 mV/cm, and DC to 40 MHz at 1 mV/cm. A $\pm$5-V comparison voltage is built in.





50 Hz-to-1 MHz SPECTRUM ANALYZER

The Type 3L5 Plug-In Unit for Type 561A and 564 Oscilloscopes operates over a center-frequency range of 50 Hz to 1 MHz, and provides accurate spectral and time-based displays from 10 Hz to 1 MHz. Deflection factors extend to 10 μV/div RMS for spectral displays, and to 1 mV/div P to P for time-base displays. Dispersion is calibrated from 10 Hz/div to 100 kHz/div. Resolution bandwidth is $\leq$10 Hz to $\geq$500 Hz.

SCOPE-MOBILE ® CARTS

Model 200-1 holds Type 454 or other portable instruments. Friction locks provide tilting from 0 to 60 degrees. Cart occupies less than 18 inches of aisle space, goes up and down stairs easily. Model 200-2 is similar, holds Type 422. Model 205-2 and 205-3 hold Type 568 or other instruments of similar size. Plug-in compartments are provided for three Letter Series or 1-Series plug-ins, or four 2- or 3-Series plug-ins.

Service Scope

USEFUL INFORMATION FOR

USERS OF TEKTRONIX INSTRUMENTS

Tektronix, Inc.
P.O. Box 500
Beaverton, Oregon, U.S.A. 97005

FRANK GREENWOOD
DEPARTMENT OF TRANSPORT
T & E SYSTEMS LAB.
BOX 4028, STATION E
OTTAWA, ONTARIO, CANADA

1/67