Tracing Tube Characteristics on a Cathode Ray Oscilloscope

This dynamic method of determining tube characteristics permits higher values of current and voltage to be used without damage to the tube under test. A simple technique, using d-c coupled amplifiers with equal phase shifts, permits accurate delineation of the curves

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THE observation of volt-ampere characteristics of vacuum tubes by means of a cathode ray tube has many advantages over the static point by point method[1]. Chief among them are the speed with which the characteristics are obtained and the safety with which the upper limits of operation are observed. The dynamic method allows higher voltages to be applied for short periods of time which are insufficient to cause damage to the tube whereas a constantly applied voltage of the same magnitude as used in the static method would be detrimental in the time necessary to observe the current values and to record them. The oscillographic observations are of great value for rapid testing of tube characteristics since the operation of the tube over its entire range of voltages is observed at a glance.

The most important characteristic of a vacuum tube is its plate current as a function of plate voltage with grid voltage as a parameter. The fundamental method of observing this characteristic on a cathode ray tube would be to apply a periodically varying voltage to the plate of the tube and the horizontal deflecting plates of the oscillograph, as in Fig. 1. A voltage which is proportional to the plate current is applied to the vertical deflecting plates. This voltage is obtained by inserting a resistor R in the plate circuit of the tube, the voltage drop across this resistor being proportional to the plate current flowing through it.

However, in order to keep the error in the determination as small as possible, the inserted resistor must necessarily be made as small as possible. It then becomes necessary to apply the voltage drop to the vertical plates through an amplifier in order to give an adequate voltage deflection.

Phase Shift

One of the chief difficulties encountered in attempting to obtain volt-ampere tube characteristics on an oscillograph is that the trace often appears in the form of a "loop" instead of a line. This is due to phase shift, as can be seen from the following considerations. If two equal sinusoidal voltages are applied to the plates of a cathode ray tube, then a straight line at an angle of 45 degrees will appear on the screen if the voltages are in phase. If, however, there is a phase shift between the two voltages so that the horizontal voltage is expressed by $x = E \sin \omega t$ and the vertical by $y = E \sin (\omega t + \theta)$ then an ellipse will appear on the screen (since by eliminating t from these equations an expression between x and y results which is the mathematical equation for an ellipse). In the limiting case of $\theta =$ zero, the ellipse degenerates into a straight line as noted above and for small values of θ, the ellipse appears as a narrow loop. It may be shown from the above equations that the maximum vertical "opening" of the loop is $2 E \sin \theta$. For a trace covering the three-inch cathode ray screen, it follows from the above that even for a phase shift of only 0.5 degree, the opening is 0.7 mm which is enough to be very annoying to the eye. This numerical illustration shows how extremely careful one must be to avoid even a very small amount of phase shift between the horizontal and vertical voltages. The phase shift is due to interelectrode or stray capacities. It can be introduced at three places in the circuit, namely: at the cathode ray

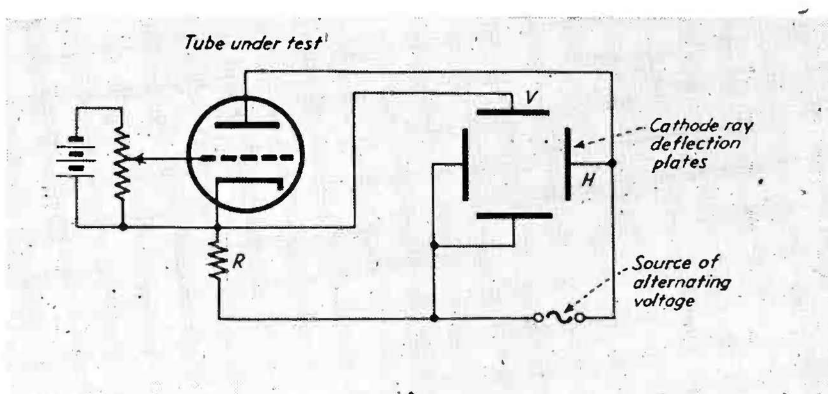


Fig. 1—Basic circuit for measuring tube characteristics oscillographically

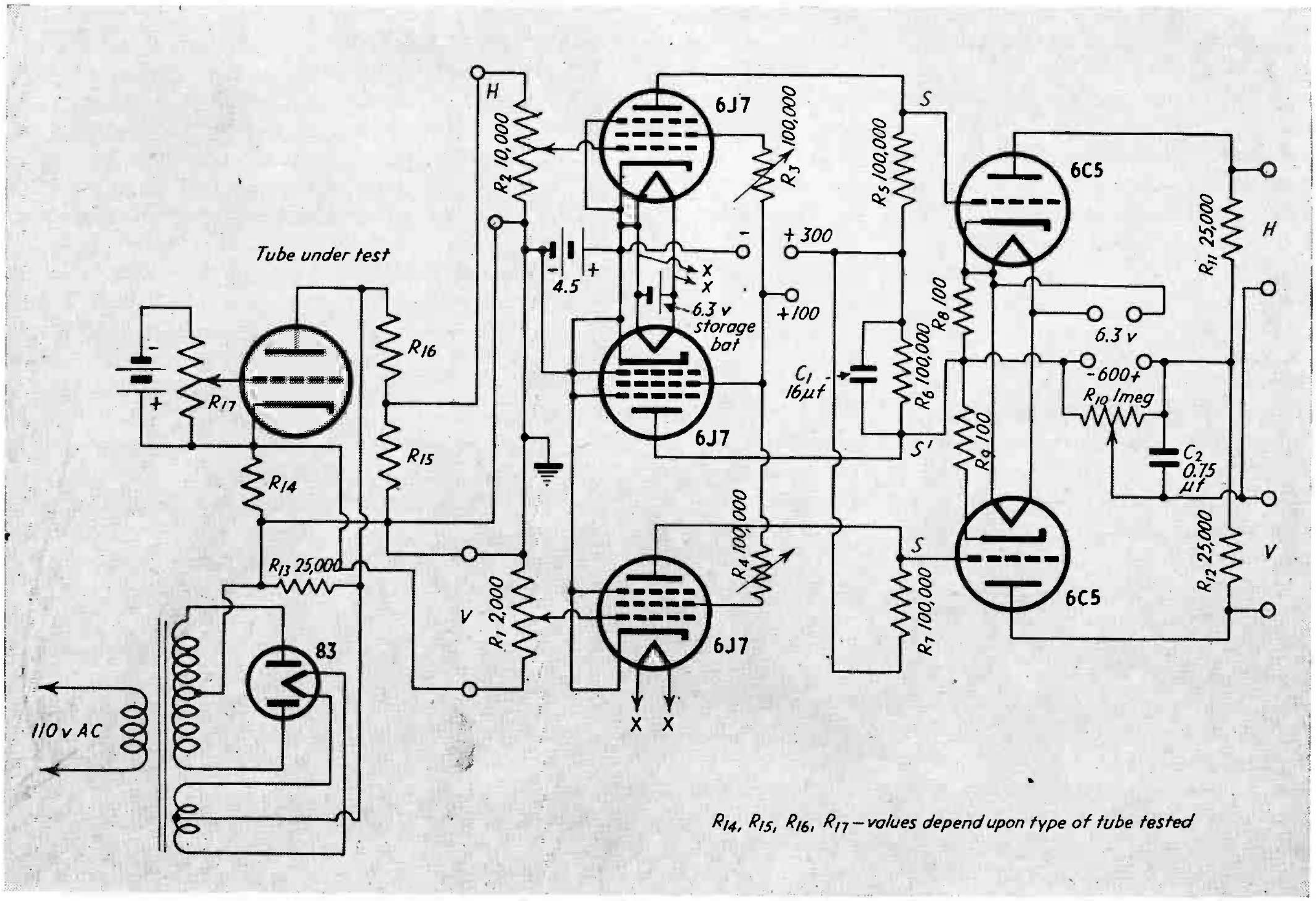


Fig. 2—Complete circuit diagram of the amplifiers used to develop the deflection voltages for the oscilloscope

tube plates, in the amplifier or in the tube under test. Each of these must be considered.

At first it would seem improbable that the tube interelectrode capacities, which are of the order of magnitude of micromicrofarads, would cause noticeable phase shift at 120 cps[2]. However, a simple calculation shows that a capacitance of 10 micromicrofarads when shunted by a one megohm resistance introduces a phase shift of 0.5 degrees which, as noted above, is excessive. This means that the resistance which shunts the cathode ray tube plates must be much smaller than a megohm in order not to produce a noticeable loop. It may be shown that the parallel combination of the load and the tube plate resistance determines the phase shift introduced at the cathode ray tube plates. By using the 6C5 triode with a load resistance of 25,000 ohms this parallel resistance was made less than 10,000 ohms which thus assured negligible phase shift.

The gain of this triode amplifier is only about 15 and hence it was preceeded by a high gain pentode (6J7) so that an overall gain of about 1000 was obtained. The grid voltage swing employed in obtaining transfer characteristics is usually too small to be applied directly to the plates of the cathoderay tube, hence an amplifier was used for the horizontal plates as well as for the vertical plates. Furthermore, by designing identical horizontal and vertical amplifiers there can be no relative phase shift between amplifiers. This was demonstrated by applying the same signal to both amplifiers. A straight line (without the slightest trace of a loop) was observed for all frequencies up to 20,000 cps.

In only a very few cases was a loop observed in measuring volt-ampere characteristics and in each case it could be traced to the tube under test. Usually by rewiring to eliminate stray capacities the loop disappeared. However, if the tube possessed large interelectrode capacities and if these were shunted by high (dynamic) plate resistances, then some phase shift was inevitable. If this phase shift was small and increased linearly with frequency, then it could be compensated for by introducing an equal phase delay into the other amplifier. This was accomplished by putting a variable capacity of the order of 1000 μμf across points *SS'* (Fig. 2) of the appropriate amplifier. Of all the tubes tested, only in one, (a phototube), was it found impossible to remove the loop. This was due to the extremely high dynamic and non-linear plate resistance of the tube which could not be compensated.

The Amplifier

If the plate volt-ampere characteristics are to be obtained at various grid voltages, the d-c component of plate current must be amplified together with the a-c component and its harmonics. If the d-c component is not amplified, the trace observed on the oscillograph screen tends to orientate itself so that the average value of deflecting voltage is zero about an axis lying along the diameter of the screen. When the grid voltage of the tube under observation is changed, the d-c plate current changes and the trace is therefore shifted from its true position relative to the trace observed at the previous value of grid voltage. This condition therefore dictates the utilization of a directly coupled amplifier.

The circuit diagram of the amplifiers, together with the tube under test is shown in Fig. 2. To permit the amplification of d-c voltages, there must be no condensers or transformers for coupling between stages. Decoupling of the quiescent d-c voltage of the preceding stage may be obtained by the use of a battery or a voltage drop across part of the power supply bleeder. However, a much more stable system results if a third tube is used to obtain the d-c decoupling voltage. This tube is used to decouple the first stage of both amplifiers as shown in Fig. 2. If all three 6J7's had identical characteristics and had equal load resistances, the grid signal voltage on the second stage would be zero when the input signal to the amplifier is zero. However, it is very difficult to obtain perfectly matched tubes and resistances so that provision is made for balancing by varying the static plate current of each 6J7 amplifier tube, by means of the screen voltage, until the voltage drop across its load resistance is equal to the drop across the balancer tube load. In practice, this is accomplished in a very simple manner. The outputs of the amplifiers are connected to the respective plates of the cathode ray tube and a spot is obtained on the screen. The point *S* on one amplifier is then shorted to *S′*. If the amplifier is not balanced, the spot is deflected. The screen grid potentiometer is then adjusted until no deflection is observed upon shorting *S* to *S′*. This procedure is then repeated for the other amplifier.

When obtaining plate volt-ampere characteristics, the amplifier is balanced as outlined above. The 6C5 tubes operate at approximately -1.5 volts bias (15 ma passing through the 100-ohm biasing resistor). This adjustment requires that the grid signal voltage of the 6C5 increase only in the negative direction to prevent the flow of grid current. The input signal voltage must therefore increase in a positive direction. The polarity of the input connections must be correctly maintained when amplifying voltages having a d-c component. If it is desired to amplify signals containing only a-c components, the 6C5's are biased at a convenient value. This is done when observing mutual transfer characteristics, as explained below.

The voltage applied to the tube under test may be of either of two forms. Since only positive voltages need be applied, the voltage may be a sinusoidal voltage having a d-c positive bias equal to the maximum a-c value, or the un-filtered output of a full wave rectifier. The latter form has been used in obtaining the pictures shown here. The method of obtaining mutual transfer characteristics is shown in Fig. 3. For this procedure, the 6C5's are biased to about -9 volts in a manner similar to the method of balancing except that a battery of 9 volts is used, maintaining the proper polarity, instead of shorting the points *SS′*. When a balance is reached, the battery is removed.

The traces on the cathode ray tube screen are centered by means of the potentiometer, R_{10}. By this control,

The oscillograms shown at the right were taken with a Kodak view camera, f/4.5 lens with Kodak Ortho Press Plates. The exposure varied between 1/5 and 1/10 second. A DuMont 34-XH tube was used

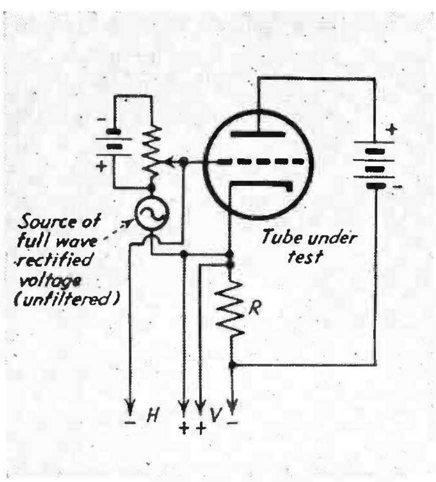


Fig. 3—Method of measuring mutual transfer characteristics

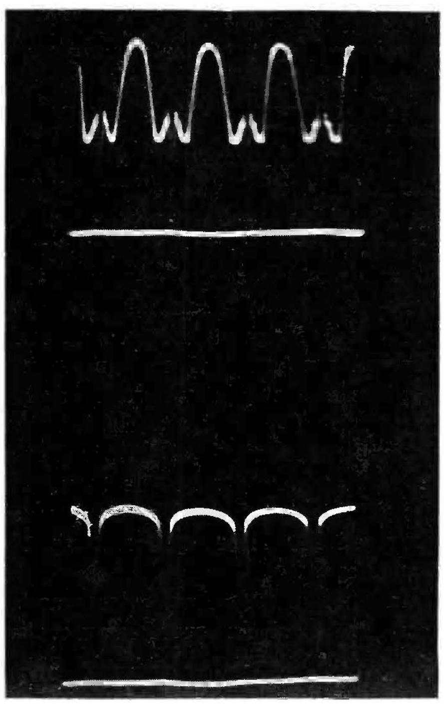


Fig. 4—Top, waveform of plate current of tetrode. Bottom, waveform of plate current of pentode. Secondary emission in the tetrode gives rise to the lower "hump," absent in the latter case

Fig. 5—Plate volt-ampere characteristics of a kenotron rectifier (type FP89), at various filament voltages

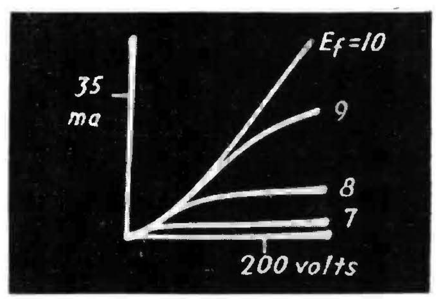
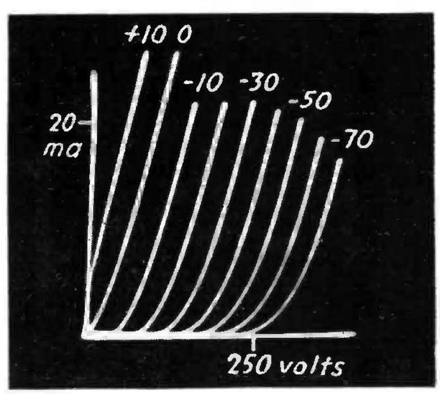


Fig. 6—Plate characteristics of type 89 tube connected as triode



the beam spot is moved across the screen at a 45-degree angle and the origin of the characteristic curves may therefore be easily placed at a corner of the screen.

The 300-volt power supply for the first stages is electronically regulated and built on the same chassis as the amplifiers[3]. However, the 600-volt supply is external and need not be regulated, although a well filtered supply is in order. All input and output cables are shielded to prevent pickup from stray fields. Because of the high gain of the amplifier, a storage battery was used as the heater voltage supply for the 6J7's. With ac on the heaters a noticeable ripple was observed on the cathode ray tube screen.

Frequency Response

In order to obtain a true characteristic curve, the amplifiers must meet the following specifications: They must be linear, must have very little frequency and phase distortion up to about the fiftieth harmonic and both amplifiers must have the same amount of phase shift and distortion. By phase shift is meant a displacement in phase angle of the output voltage relative to the input voltage, for a sinusoidal input. By phase distortion is meant the lack of proportionality between frequency and phase shift of the output voltage relative to the impressed voltage. Tests on the amplifiers described show that they meet these specifications.

The plate current of the tube under test is usually far from sinusoidal. The wave shapes for the plate current in a tetrode and pentode (with applied rectified a-c plate voltage) are shown in Fig. 4. In the extreme case of the pentode, the wave shape is close to being square. It has been experimentally determined by means of filters that all harmonic frequencies up to the fiftieth should be reproduced in order to preserve the original wave shape with accuracy.

The amplifiers proved to have a flat frequency response up to 2000 cps and the gain dropped off 7 per cent at 6000 cps, the voltage gain of each amplifier being 1000. The fundamental frequency used in plotting the curves was 120 cps and the fiftieth harmonic is therefore 6000 cps. The magnitude of the fiftieth harmonic for a square wave is a very small percentage of the fundamental magnitude, so that the decrease in gain is negligible relative to the fundamental.

If a flatter frequency response were desired, it can be obtained easily at the sacrifice of gain. Changing the load resistances of the 6J7's to 20,000 ohms instead of 100,000 resulted in a voltage gain of 230 and a frequency characteristic which dropped 8 per cent at 20,000 cps.

The photographs shown in Figs. 4 to 10 were obtained by taking one exposure for each parameter. This simplifies the procedure, since only one trace is obtained at a time. In order to obtain all the traces at once it would be necessary to use either a rotating or an electronic switch[1].

Calibration of the photographs is an easy matter. If the vertical voltage is removed a horizontal axis is traced whose length corresponds to the maximum value of the voltage used. To obtain the current calibration a voltage is fed into the vertical amplifier and the horizontal voltage is removed, resulting in a vertical trace whose length corresponds to the voltage input. Since the value of resistance inserted in the test tube circuit is known, the vertical axis is calibrated in terms of current.

An alternate method of calibration is to determine a point on the volt-ampere characteristic for a given value of grid voltage and a d-c value of plate voltage equal to the maximum a-c value used. The plate current is noted and the end point of a trace for the given grid voltage is located. All other points can be found by proportion.

The value of this technique cannot be overemphasized. Its application to vacuum tube research and design has been recognized by many. The method is also a convincing test of the characteristics of tubes and their adaptability in circuits.

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Fig. 7—Plate characteristics of type 6J7 tube connected as tetrode

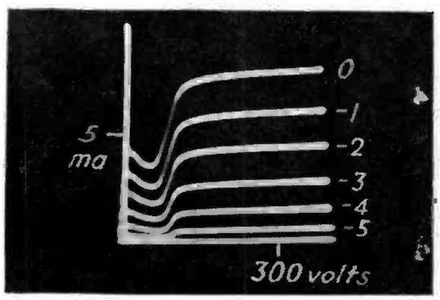


Fig. 9—Mutual transfer characteristics of 6J7 and 6K7. Plate voltage is 250

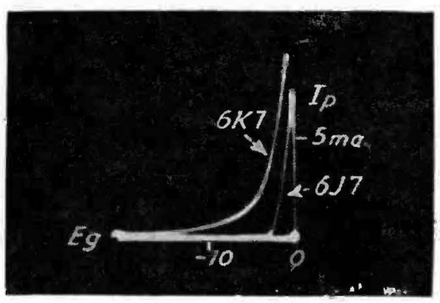


Fig. 8—Plate characteristics of type 6J7 pentode

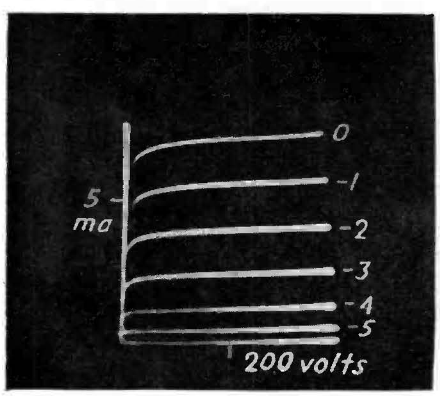
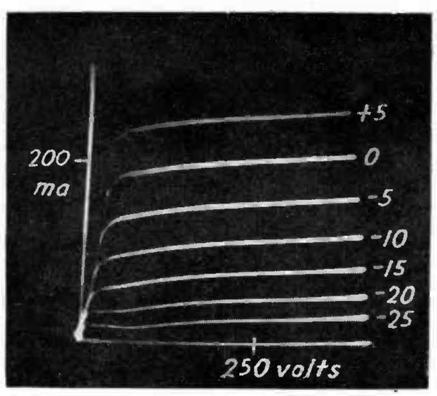


Fig. 10—Plate characteristics of beam power tube, type 6L6



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