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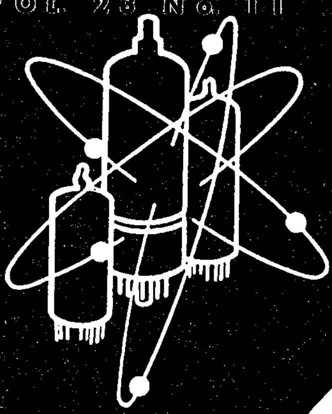

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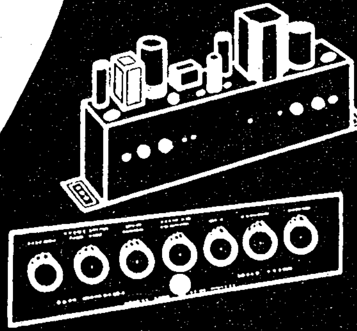

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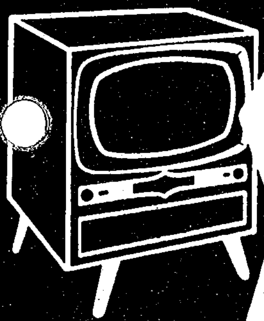

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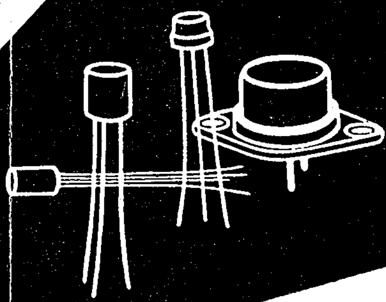

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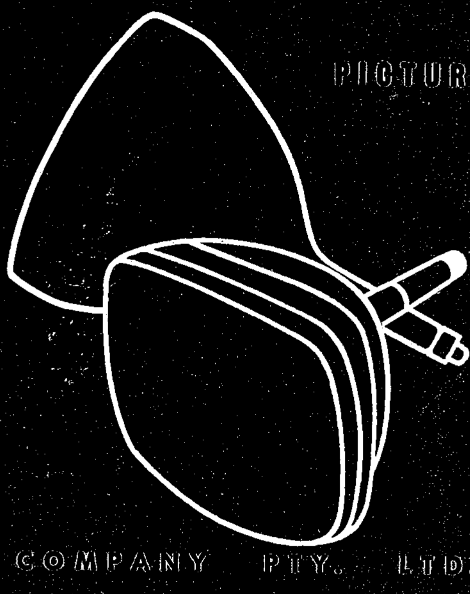

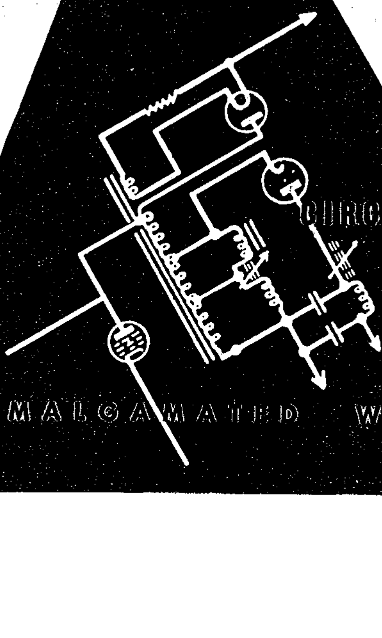

CIRCUITRY

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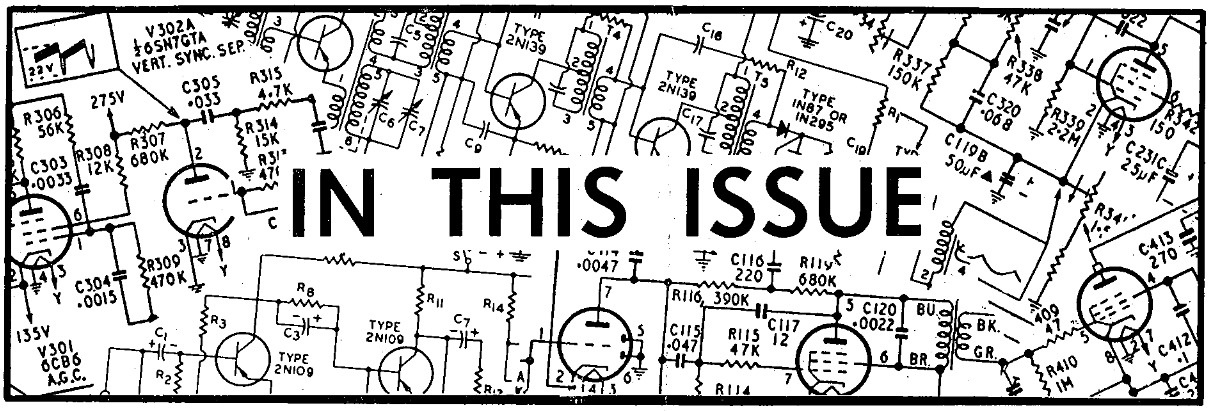

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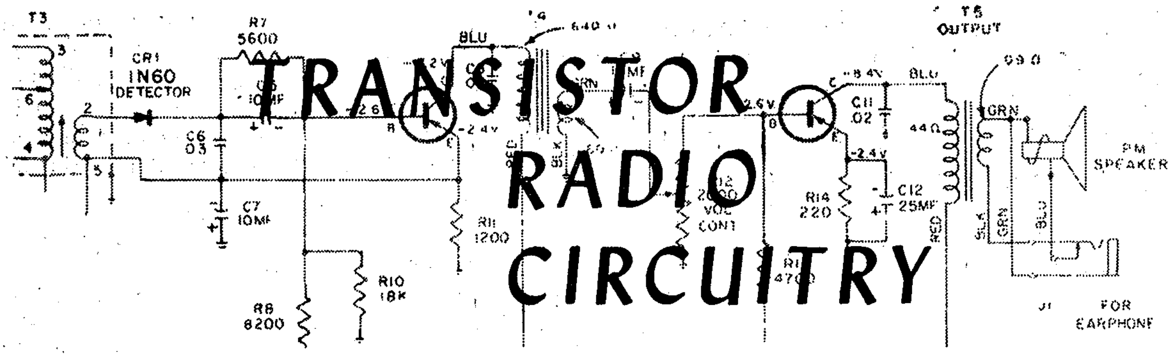
TRANSISTOR RADIO CIRCUITRY



Introduction

Servicing of anything becomes easier if we understand how it works. A serviceman must understand the conditions which exist in the circuits of a transistor radio if he is to be able to render efficient service on them.

The serviceman is familiar with the operating conditions which exist in thermionic valve circuits and it will be of great assistance to compare such circuits with transistor circuits. Throughout the text of this article there will be frequent comparisons of circuit conditions and their comparative effect on service problems.

General Circuit Conditions

Junction transistors used in transistor radios may be compared with thermionic valves such as type 6C4. In this triode valve there are three active elements: GRID-CATHODE-PLATE. In a transistor there are also three comparable active elements: BASE-EMITTER-COLLECTOR. Signal amplification in both the valve and the transistor is accomplished by applying a small variable voltage to the input circuit in such a manner that it will control the flow of current in the output circuit.

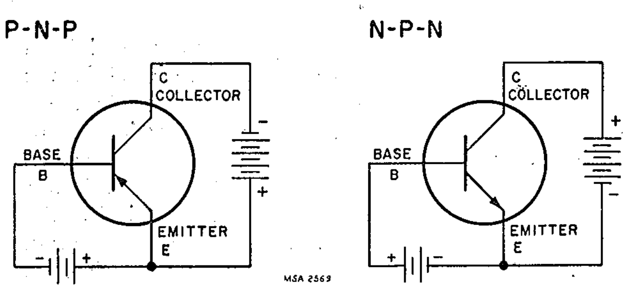


Fig. 1. Schematic Diagrams of Junction Transistors.

Figures 1A and 1B are schematic symbols of junction type transistors. The base element is represented by a heavy short line perpendicular to its connecting lead. The line drawn at an angle to the base without an arrowhead represents the collector and the line drawn at an angle to the base with an arrowhead represents the emitter. If the arrowhead points away from the base as in Figure 1B it indicates an n-p-n type of transistor. So far as service problems are concerned it only denotes reversed polarity of the terminal voltages and reversed direction of current flow.

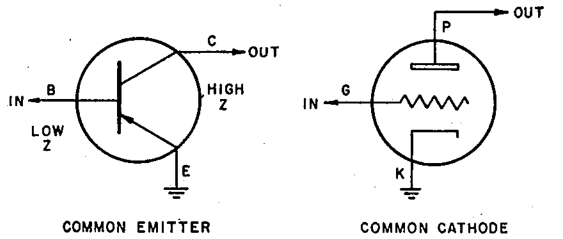


Fig. 2. Transistor Circuit Comparison with Equivalent Thermionic Valve Circuit.

In general, the emitter of a p-n-p transistor can be likened to the cathode of a valve in that it is the source of current flow. The base, more or less controlling the current flow, is equivalent to the grid of the valve. As the collector is the part of the transistor through which the current flow leaves the unit, it can be considered as serving the same function as the valve plate. The elements of an n-p-n transistor serve the identical purposes but the direction of current flow is reversed. The most commonly-met transistors are p-n-p types.

Figure 2 is the most commonly used transistor circuit. It is the "common emitter" circuit and is equivalent to the most widely used valve circuit, that of "common cathode". As used in transistor radios, the "common emitter" circuit has a comparatively low input impedance and high output impedance. Like its valve counterpart, it provides phase inversion.

The transistor circuits which are equivalent to "grounded grid" and "cathode follower" valve circuits are little used in radios, and will not be described in this text.

Figure 3 illustrates the gramophone pre-amplifier circuit used in a typical high-fidelity instrument. The upper part is the complete circuit and the lower part is the equivalent three-terminal network. As used in these receivers, the "common emitter" circuit matches a low-impedance pickup to valve input. It combines high gain with low hum; a very desirable combination.

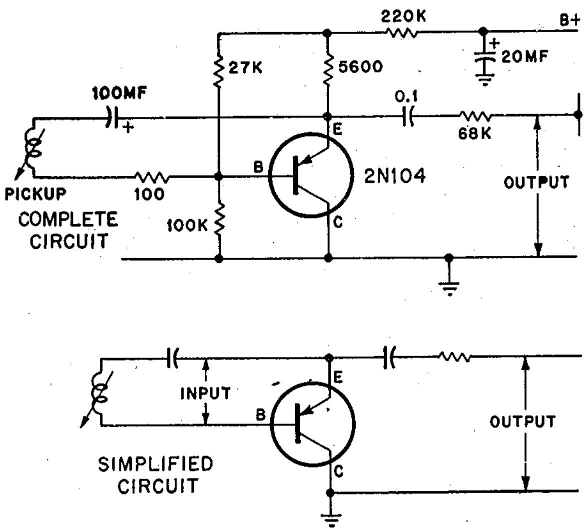


Fig. 3. Typical Gramophone Pre-amplifier Circuit.

Terminal Voltages

Before proceeding with other circuit conditions, it is desirable that there be a comparison of terminal voltages. In the first place there is no heater or filament to be supplied with power. Secondly, in transistor radios, the normal maximum voltage encountered is only nine volts. However, more important than the maximum voltage is the bias voltage. This is the voltage between base and emitter and corresponds to grid voltage in valve circuits. The bias voltage is of a magnitude of 0.05 to 0.2 volt and is relatively critical. Servicemen who are not accustomed to working with such low voltages may overlook the fact that 0.05 volts ± 20% amounts to 0.04 volts to 0.06 volts.

The third major difference is polarity. Servicemen are accustomed to positive voltages on the plate and negative voltages on the grid in respect to a common cathode. With p-n-p transistors both the collector and the base voltages are negative in respect to the common emitter. The polarity of n-p-n transistors is reversed — both are positive in respect to the emitter.

In respect to bias voltages of agc controlled transistors, agc decreases the bias voltage (base to emitter) regardless of polarity; with zero bias there is practically no current flow. A transistor behaves much like a sharp cutoff valve. Figure 4 illustrates the relationship between bias voltage and collector current in a p-n-p transistor.

Unlike a thermionic valve, which in the usual Class "A" service does not draw grid current, the base terminal of a transistor does draw a slight current in normal operation. Class "B" audio output circuits are also extensively used in transistor radios and will be described later in this text.

Circuit Comparison

To enable a serviceman better to understand the operation of transistor radios, a stage-by-stage comparison should be made between circuits of current models of transistor radios and the equivalent thermionic valve circuits.

The first circuit to be compared is the converter circuit. In the commonly used valve pentagrid converter, the oscillator signal is coupled to the antenna signal inside the valve. In the early days of radio, triode converter valves were used and such a circuit is shown in Part A of Figure 5. In both a triode valve circuit and in a transistor circuit, the oscillator signal must be coupled to the input circuit outside of the valve or transistor. A typical converter circuit is shown in part B of Figure 5; this circuit uses an n-p-n transistor.

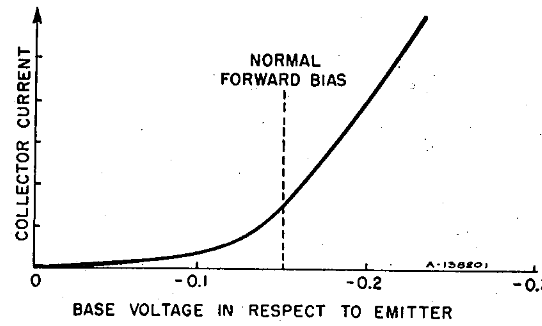


Fig. 4. Bias Voltage vs. Collector Current (P-N-P Transistor).

As illustrated, part of the oscillator coil is in series with the converter output to provide the usual feedback for oscillator operation. As mentioned previously, the input impedance of "common emitter" transistor circuits is quite low. To prevent loading of the antenna and oscillator tuned circuits these circuits must be coupled to the converter input through low impedance coupling coils. These coupling coils are in series with each other. Other converter circuits are similar, differing mainly in voltages and values of circuit components.

In the conventional thermionic valve oscillator circuit, oscillator operation can be checked by measuring the developed dc bias across the oscillator grid resistor. There is no comparable resistor in the transistor circuit. Oscillator voltage must be measured either with an rf voltmeter or a calibrated oscilloscope. There should be an

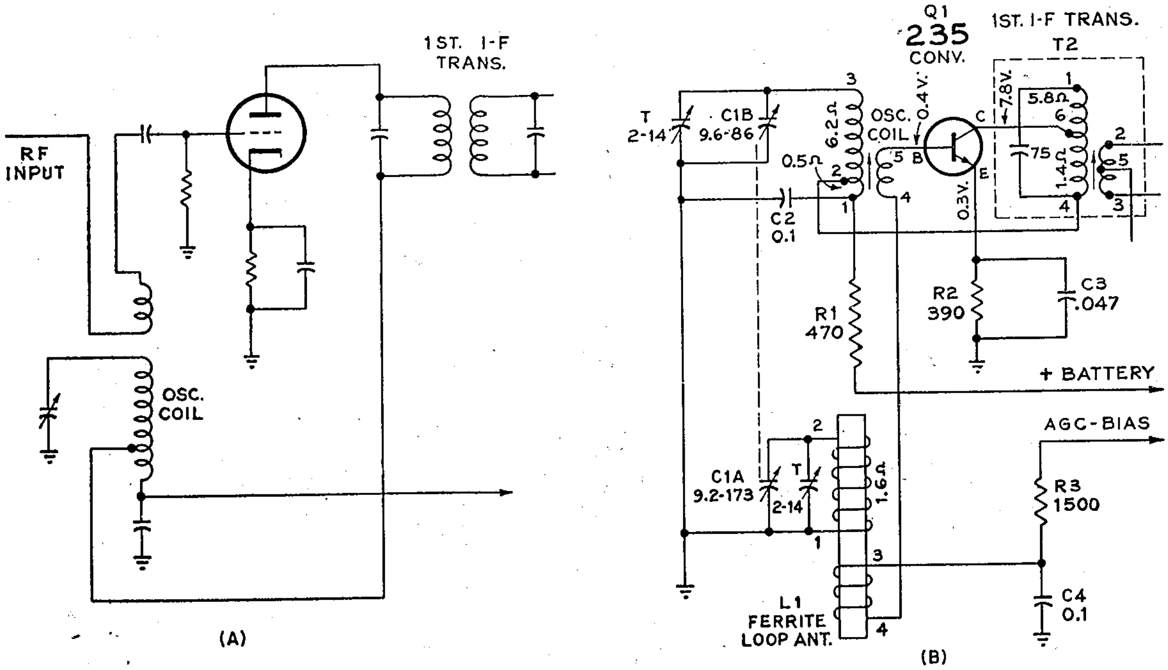


Fig. 5. Transistor Converter Circuit Compared with Triode Valve Converter Circuit.

oscillator voltage of from 0.07 to 0.25 volts rms (0.20 to 0.70 volts pp) at the converter base.

At this point it should be mentioned that although an if signal can be directly injected at the converter input, an rf signal can be injected only by radiating it to the ferrite antenna. The very common practice of touching a finger to a grid to determine if a stage is "alive" cannot be employed with transistors, because the low impedance input is less susceptible to such circuit loading.

The next circuit to be examined is the if amplifier. Figure 6 is a schematic diagram of a typical if amplifier circuit, also notable in using n-p-n transistors. Two stages of if amplification are used to obtain sufficient gain and selectivity and yet

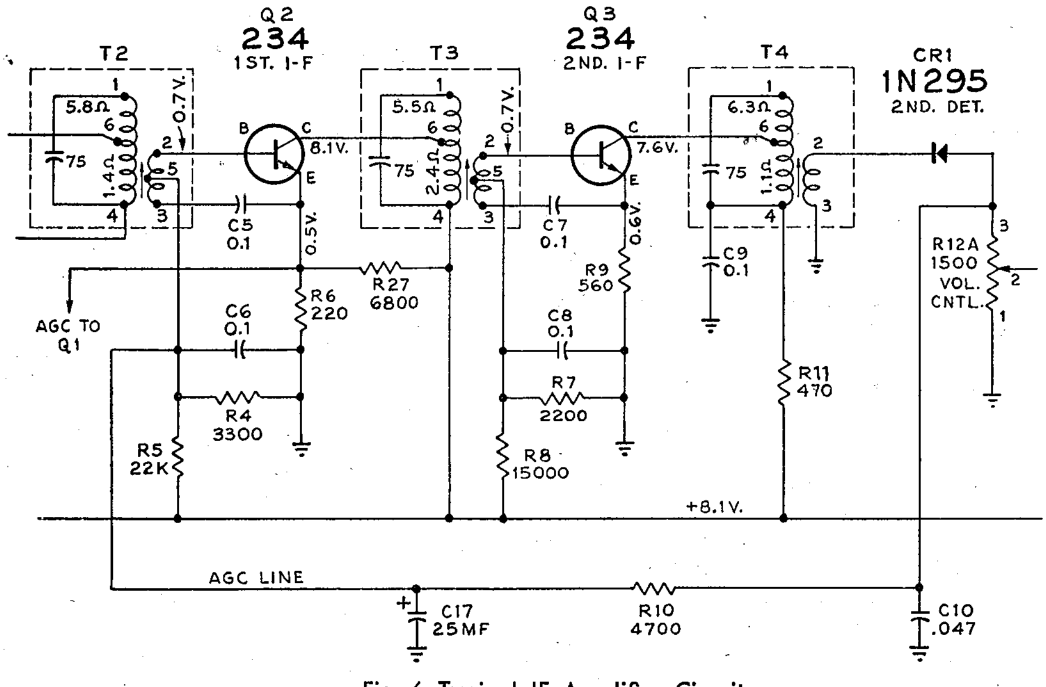


Fig. 6. Typical IF Amplifier Circuit.

maintain a high degree of circuit stability. The primary is tapped in order to obtain high Q and to provide maximum power transfer. The load impedance of the transistor is about 30,000 ohms, that of the resonant circuit about 700,000 ohms. The input impedance of Q2 is very low and to obtain maximum power transfer the transformer must be a step-down to match the approximate 40 ohm input.

to offset the sharp cutoff characteristics of the transistor.

The agc line resistor R10 and capacitor are unusual in size when compared with equivalent components in thermionic valve circuits. It was previously noted that a slight current flows in the base circuit of transistors. In order to have effective agc, the circuit impedance must be kept low. The agc time constant of the 4700 ohm resistor and

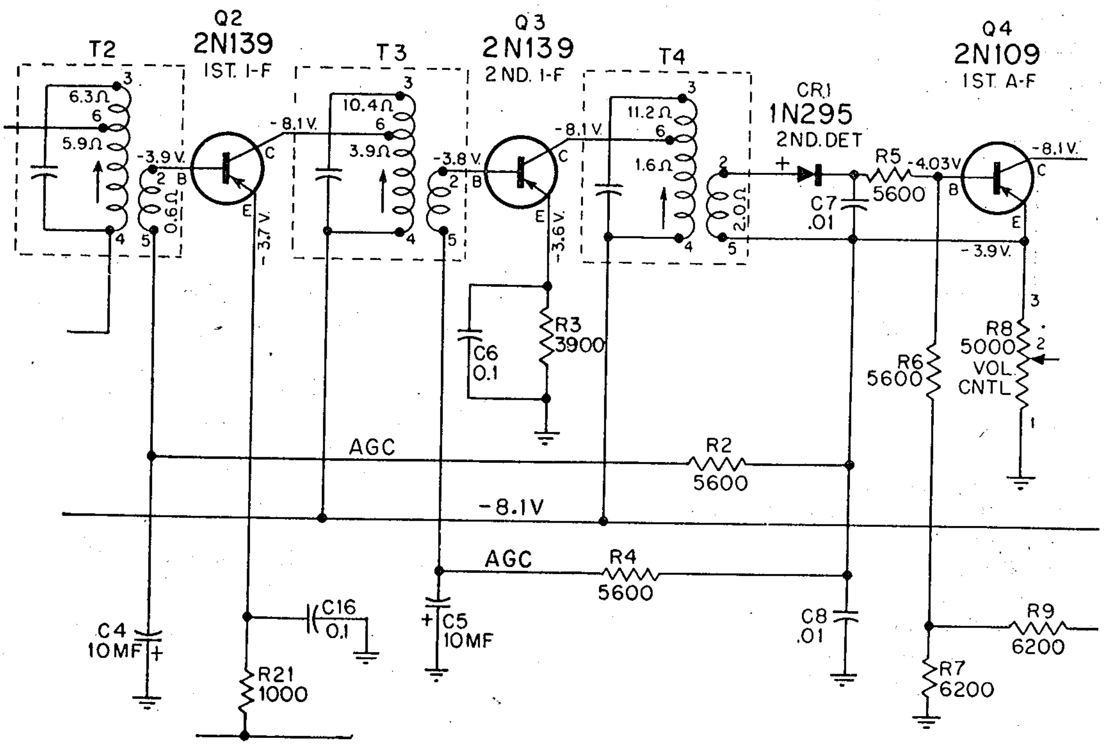


Fig. 7. Typical IF Amplifier Circuit.

In much the same manner as in the old-time radios using triode valves as rf and if amplifiers, the secondaries of the if transformers are tapped for neutralization purposes. Capacitor C5 provides a feedback path from the emitter of Q2. The amount of feedback is not controlled by an adjustable capacitor as was customary in valve radios, but is taken care of in the transformer design. The value of C5 is not critical but must provide a low impedance signal path from the emitter to the transformer.

Resistors R6 and R9 in the emitter circuits provide bias voltages much like cathode resistors in valve circuits. Assume that signal input creates agc voltage and reduces the base voltage of Q2 from 0.7 v. to 0.65 volts; this reduces the emitter current and thus the emitter voltage from 0.5 v. to possibly 0.48 v. In this instance the base voltage has changed 0.05 v. but the bias voltage has only changed 0.03 v. This self-regulating action helps

25μf capacitor is the same as for a combination of 4.7 megohms and 0.025 μf.

$$4700 \times 25 = 4{,}700{,}000 \times 0.025$$

Figure 7 is a schematic diagram of a second typical if amplifier circuit. It will be noted that "split input" if transformers are not used in this circuit. Circuit stability is obtained through a change in the transistor output loading and higher values of resistance in the emitter circuit. This results in a simpler and more economical circuit. Other differences which should be noted are (1) the use of p-n-p transistors, (2) reversed polarity of terminal voltages and (3) agc is applied to both if amplifiers and not to the converter.

The circuit of Figure 8 uses only one if amplifier stage. It will be noted that a crystal diode is used in this circuit and is designated as "OVERLOAD DIODE". As mentioned previously, transistors have

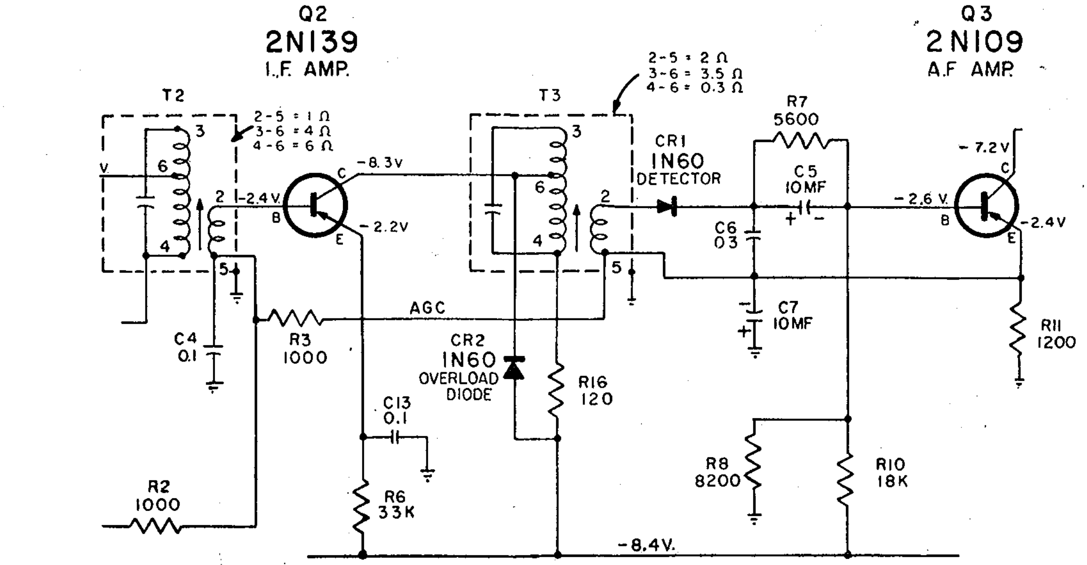


Fig. 8. Typical IF and Detector Circuit.

a sharp cutoff characteristic and this diode is added to give better agc action. The voltage across resistor R16 is about 0.12 volts and delays the conductance of this diode until the signal level is greater than the delay voltage. When the diode conducts, it lowers the Q of the transformer thereby reducing the power gain. The if transformer feeding into the detector crystal diode is very much like the preceding transformers, except that the secondary is designed to match the approximately 2000 ohms impedance of the detector diode.

Figure 9 is a schematic diagram of the detector, volume control and 1st audio circuits of the set shown partly in Figure 6. A crystal diode rectifier is used as a second detector. The detector action is identical to conventional detector circuits (both crystal diode and thermionic diode). However, since it feeds into a low impedance presented by Q4, a low resistance volume control (R12A, 1500 ohms) is used, a larger demodulating capacitor (C10, 0.047 μf) is consequently required and a large blocking capacitor (C11, 10 μf) is necessary. A dual volume control is used to provide adequate control of volume in strong signal areas. The rectified signal voltage across the first volume control is applied to the base of the 1st if transistor for agc purposes.

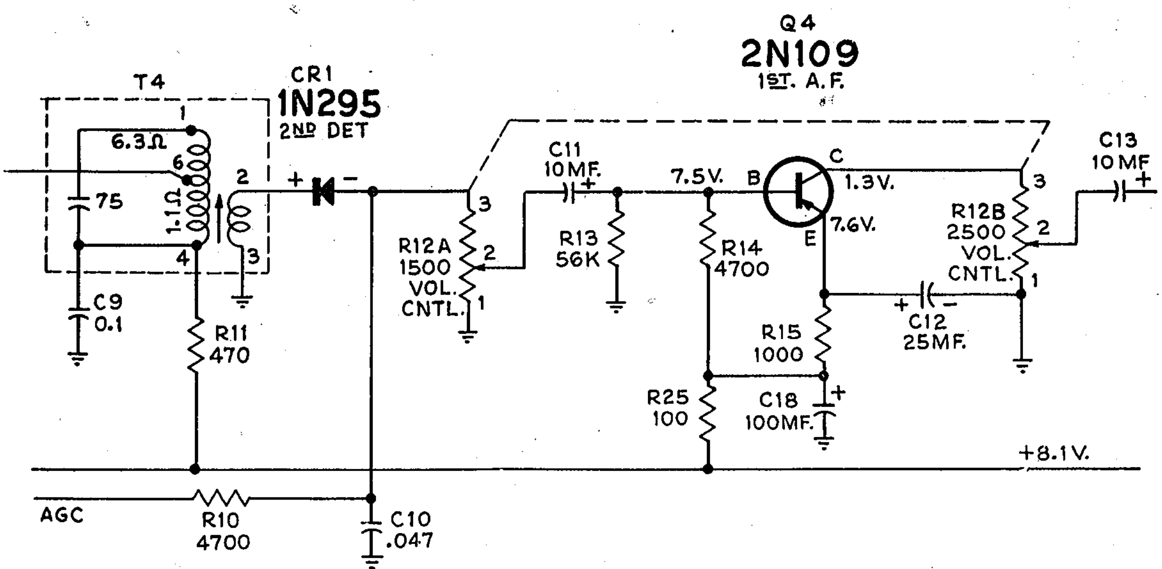


Fig. 9. Detector, Volume Control and 1st AF Amplifier in a Typical Circuit.

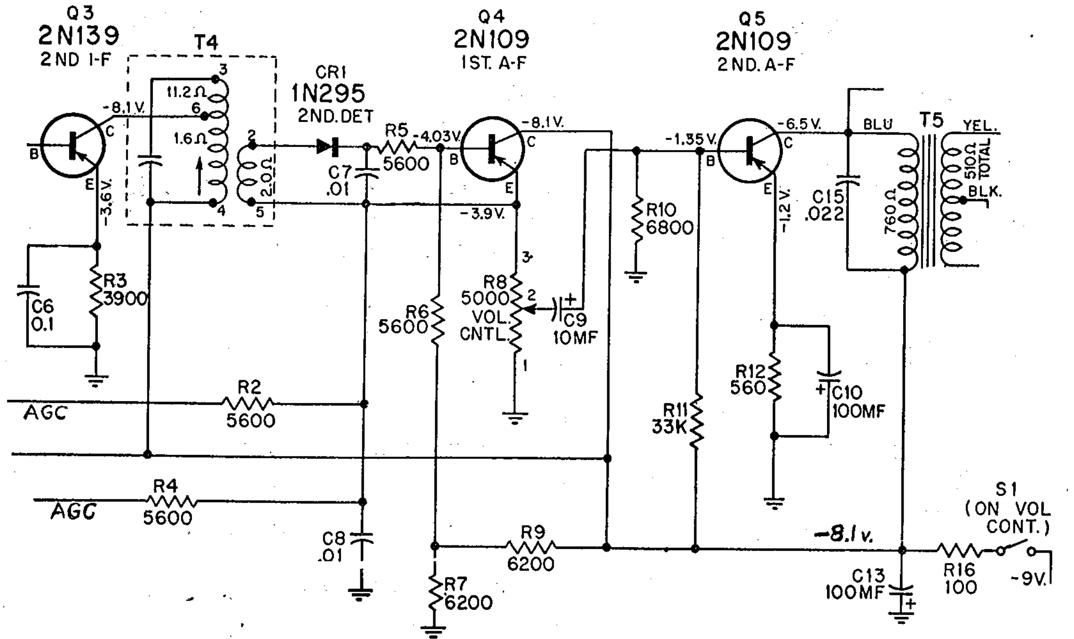


Fig. 10. A Further Typical Detector, Volume Control and 1st AF Amplifier Circuit.

Figure 10 is a schematic diagram of the detector, volume control and 1st audio circuits of the set of Figure 7. There are several significant differences. Because of the use of p-n-p transistors in the converter and if stages, a positive agc voltage must be supplied instead of a negative voltage as in the previous case. Both ends of the detector diode are above ground potential to enable the proper agc voltage to be supplied to the controlled transistors. The 5600 ohm resistor R5 applies the forward bias which is necessary with crystal diode detectors to improve efficiency and

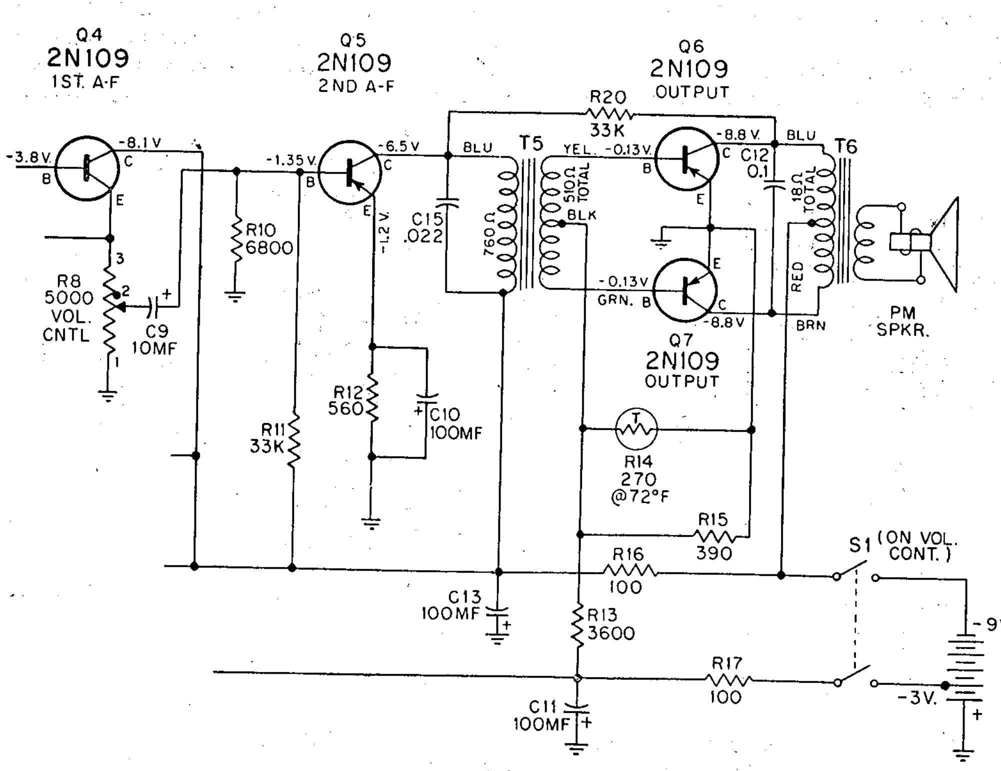


Fig. 11. Audio Driver and Output Circuit.

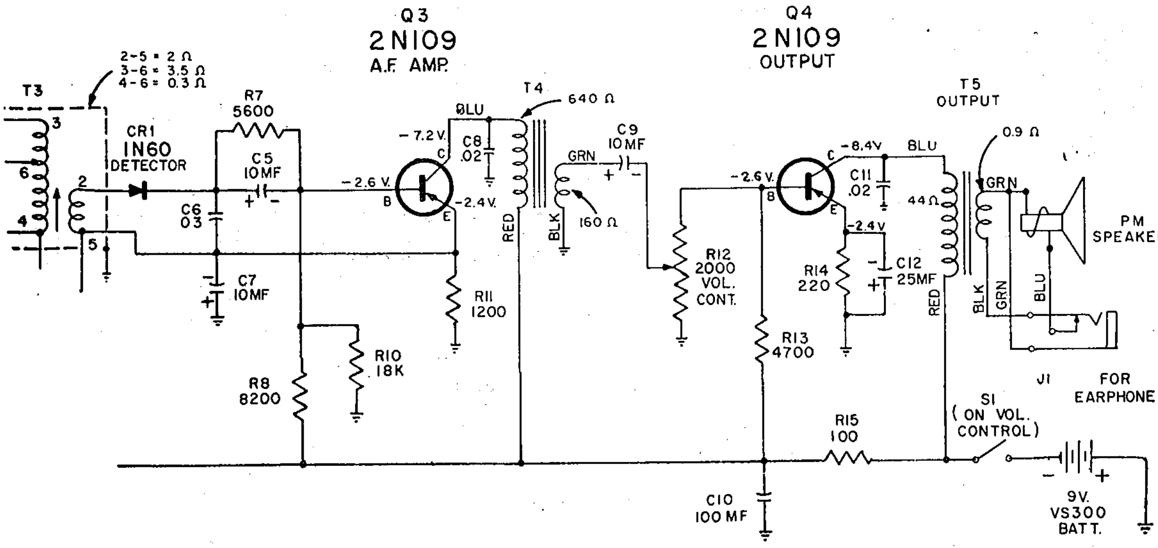


Fig. 12. A Further Typical Audio Circuit.

to prevent low signal distortion. With increased signal the voltage across R8 decreases; thus the agc voltage becomes less negative with increase of signal. At the same time the voltage across R5 increases to maintain a uniform bias on the 1st af transistor.

A second significant difference between the first audio circuits of Figures 9 and 10 is that only a single volume control is used in the latter; this volume control is in the emitter circuit. The collector is connected directly to the battery circuit. Although the collector is at ground potential insofar as audio signal is concerned, this is a "common emitter" circuit since the input signal is applied between base and emitter and the output signal exists between collector and emitter.

The first audio amplifier in both Figure 9 and Figure 10 is Class "A" operation similar to the audio amplifier stages in most radios. In line with previous explanations, it will be noticed that circuit impedances are much lower than in thermionic valve circuits; note in particular that 10 μf electrolytic capacitors are used for audio coupling.

Figure 11 is a schematic diagram of the audio driver and output stages of the set of Figures 7 and 10. A step-down transformer is used for interstage coupling. The driver operates as a Class "A" amplifier whereas the push-pull output stage operates essentially as a Class "B" amplifier. Although the terms Class "A" and Class "B" are used in describing transistor circuits because of their similarity to such thermionic valve circuits, it is well to remember that there is a slight dc current flowing in Class "A" transistor input circuits even with no signal input. The collector current in Class "A" transistor circuits is essentially constant as is the plate current in Class "A" thermionic valve circuits. In Class "B" transistor circuits, the collector current increases greatly with strong signal input in much the same manner as the plate current in Class "B" thermionic valve circuits. The dc resistance of Class "B" input circuits must be low because of this variable current.

The bias voltage supply circuit is quite critical in design. Although the bias voltage must be constant, the circuit must also afford protection for the transistors. An emitter resistor cannot be used for self-regulation in Class "B" circuits because it would result in distortion and loss in power sensitivity. Because of the fact that the conductivity of transistors increases with temperature increase, a negative temperature coefficient resistor is used in the bias circuit to decrease the bias when the temperature increases. Extreme precautions must be taken to prevent even momentary short-circuits in Class "B" transistor circuits which would increase the bias. Such a short-circuit of only a few seconds duration may permanently damage the output transistors.

The bias voltage in a Class "B" transistor circuit is quite critical and therefore the components in the bias supply circuit must be held to close limits. An illustration of this is with resistor R13 in the circuit of Figure 11. Distortion will result if the resistance value is much above 3600 ohms; if the resistor is less than 3300 ohms, the power handling ability is reduced, the no-signal collector current increases and battery

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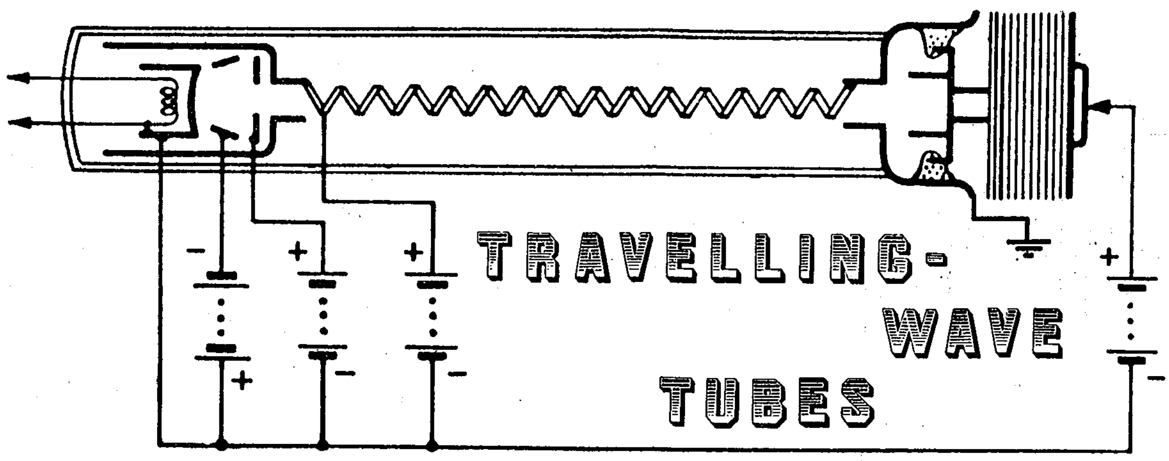


PART 4

CONCLUSION

MEASUREMENT OF PARAMETERS

In general, measurement techniques used to evaluate travelling-wave tubes are similar to those used with more conventional amplifiers. However, because travelling-wave tubes are wide-band devices, careful consideration must be given to the bandwidth requirements of associated equipment such as detectors, loads, and input and output transducers. At frequencies below 4000 Mc/s, it is often convenient to employ coaxial circuit components because of their inherent wide-band characteristics. At frequencies above 4000 Mc/s, the use of waveguide components becomes increasingly convenient.

Operating Voltages

Operating voltages of a travelling-wave tube are measured by conventional methods and conventional equipment. Appropriate safety precautions should be taken, however, to protect meters from damage in the event of short circuits.

Gain

Gain is normally measured by the substitution method. Either a precision attenuator or a calibrated power-output indicator may be used. For low-level gain measurements, a sensitive receiver must be used as the detector. The use of a precision attenuator is also desirable for such measurements because the linearity characteristic of the detector need not be known for this method. Output power of high-power travelling-wave tubes may be measured calorimetrically or directly by means of a bolometer, either alone or in conjunction with suitable directional couplers.

A block diagram of equipment used for measuring gain is shown in Fig. 20. During gain measurements, the switch is turned to position 1, the precision attenuator is set to provide minimum attenuation, and the signal generator is adjusted to provide a convenient level of detector output. The switch is then turned to position 2 to send the signal through the travelling-wave tube amplifier. Attenuation is inserted until the detector-output level is identical to that which was obtained without the travelling-wave tube in the circuit. The gain of the travelling-wave tube is directly equal to the amount of added attenuation.

It is also possible to measure gain by adapting the if attenuator technique described below for measuring noise figure.

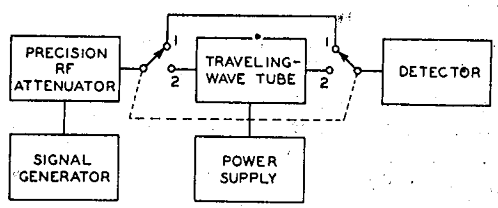


Fig. 20. Block Diagram of Gain-measuring Equipment

Noise Figure

The noise figure, F, of an amplifier is given by

$$F = \frac{S_1/N_1}{S_o/N_o}$$

where S_1/N_1 is the signal-to-noise ratio at the input terminals and S_o/N_o is the signal-to-noise ratio at the output terminals. The test system is set up as shown in Fig. 21 so that the output noise of the travelling-wave tube registers on the meter. The noise source is turned on, but the rf attenuator between the noise source and the travelling-wave tube is set for about 40 db. The rf attenuation is then removed, and the precision if attenuator is adjusted until the receiver output reaches its previous value. The power ratio equivalent to the if attenuation thus added is inversely proportional to the noise generated in the travelling-wave tube.

The power ratio corresponding to the added if attenuation, the effective noise-temperature ratio of the noise source, the insertion loss of the noise source, and the circuit loss between the noise source and the input to the travelling-wave tube all enter into the measurement of noise figure, as follows:

$$F \text{ (in db)} = 10 \log_{10} \frac{\left(\frac{T_B}{T_o} - 1\right)\left(\frac{L-1}{L}\right)}{(A) \cdot (Y-1)}$$

where T_B/T_O is the effective noise-temperature ratio of the gas-tube noise source, L is the power ratio corresponding to the noise-source insertion loss, A is the power ratio equivalent to the circuit loss between noise source and tube, and Y is the power ratio corresponding to the attenuation added in the precision if attenuator.

The value of the first term in the numerator of this equation is equivalent to 15.28 db for an argon-bulb, waveguide-type noise source in the 3000-megacycle region. This type does not require any temperature compensation.

As an example, the values of A and L for an equipment are 0.54 and 15 db, respectively. These db values are converted into power ratios and substituted in the equation above to give the following expression for noise figure, F, in db:

$$F \text{ (in db)} = 10 \log_{10} \frac{28.9}{Y-1}$$

If great accuracy is desired, the noise added by the receiver should be subtracted from the over-all noise figure. This correction can be calculated from the following formula for the noise figure, F_{1+2}, for two networks in cascade:

$$F_{1+2} = F_1 + \frac{F_2 - 1}{G_1}$$

In this formula, all parameters are expressed as power ratios. F_1 is the noise figure of the travelling-wave tube, F_2 is the noise figure of the receiver, and G_1 is the gain of the travelling-wave tube. When F_2 is small and/or G_1 is large, this correction is negligible.

Input and Output VSWR

Although the use of a conventional slotted line permits accurate measurement of VSWR, this technique of measurement and adjustment can be rather tedious for wide-band travelling-wave tubes and associated microwave components. Swept-frequency reflectometers and swept-frequency long-line techniques permit instantaneous visual display on an oscilloscope of VSWR as a function of frequency.

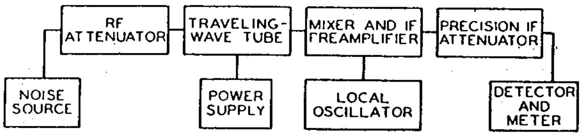


Fig. 21. Block Diagram of Noise-figure Test Set.

Cold Insertion Loss

The extent to which a signal is attenuated in a travelling-wave tube when no beam current is flowing is called the cold insertion loss. This loss is measured with the same equipment used for measurement of gain, but the procedure is reversed. Output-signal level is adjusted with the travelling-wave tube in the circuit and the attenuator set at minimum attenuation. The tube is then removed from the circuit and attenuation is inserted until the output level returns to its original reading. The amount of attenuation inserted is directly equal to the cold insertion loss.

When values of attenuation as high as 80 to 100 db are to be measured, it may be necessary to increase the input signal to a level of about 1 watt because of limited detector sensitivity. It may also be necessary to use two attenuators in tandem, because the maximum attenuation obtainable with conventional attenuators is approximately 40 to 50 db. When higher orders of attenuation are to be measured, extreme caution must be exercised to prevent direct leakage from the signal source to the detector around the desired signal path.

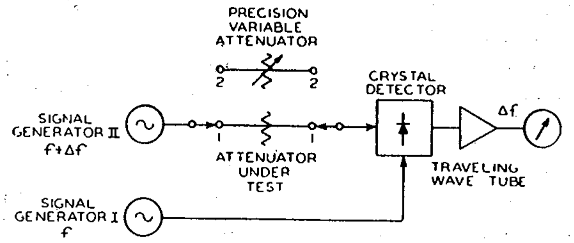


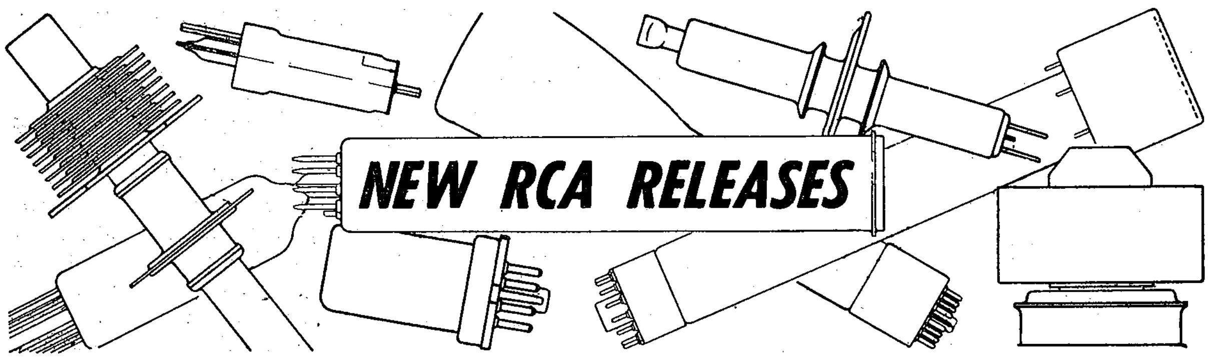
Fig. 22. Method of Increasing Detector Sensitivity for Measurement of very high orders of Attenuation.

For values of attenuation in the order of 60 db and a generator output of 1 milliwatt, the use of a crystal detector in conjunction with a tuned VSWR amplifier is satisfactory. The signal generator should be modulated with a 1000-cycle square wave. The limiting factor is the noise level of the conventional VSWR amplifier. For higher orders of attenuation, the detector sensitivity can be increased by the use of a low-noise travelling-wave-tube amplifier ahead of the detector to amplify the attenuated signal.

In the system described above, the crystal operates as a square-law device at low signal levels. It is possible to increase the sensitivity of the crystal detector by about 40 db by the use of the system shown in Fig. 22. Signal generator II may be eliminated by substituting a single-sideband modulator (fed from signal generator I) which offsets the signal frequency from signal generator I by an amount Δf. This single-sideband modulator could take the form of a saw-tooth phase-modulated travelling-wave tube, as described previously.

Phase Shift

For certain phase-sensitive applications, it may be desirable to measure the phase shift experienced by a signal as it passes through the travelling-wave tube. A suitable method for measuring such phase shift has been described by Bray, Proc. I.E.E., July 1st, 1952.



RADIOTRON 6655-A

The Radiotron 6655-A is an improved and superseding version of the 6655 multiplier phototube. The new type features improved pulse-height resolution, reduced transit-time variation, minimum cathode - luminous sensitivity of 50 μa/lumen (instead of 40 μa/lumen for the 6655), higher current amplification, and low dark-current over a wider range of operating voltages. These improvements result in superior performance by the 6655-A in scintillation counters.

The spectral response of the 6655-A covers the range from about 3000 to 6500 angstroms, with maximum response occurring in the blue region at approximately 4400 angstroms. Operated at a supply voltage of 1000 volts, the 6655-A has a median luminous sensitivity of 50 amp/lumen and a current amplification of 9 x 10^5.

RADIOTRON 2N586

The 2N586 is a germanium p-n-p alloy-junction transistor, intended for use in low-speed switching applications. It is particularly useful as a relay-actuating device and in voltage-regulator, multivibrator, dc-to-dc converter, and power supply circuits. The 2N586 may also be used as an audio oscillator and as a large-signal class A or class B push-pull audio amplifier.

Featuring excellent stability and exceptional uniformity of characteristics, the 2N586 can withstand a maximum collector-to-base voltage of —45 volts, a maximum collector current of —250 milliamperes, and a maximum collector dissipation of 250 milliwatts. These features in addition to a dc current transfer ratio of 60 at a collector-to-base voltage of —1 volt make the 2N586 particularly useful in "on-off" control applications.

RADIOTRON 7163

The 7163 is a cadmium-sulphide photoconductive cell designed for use in street-lighting control and other light-operated relay applications in industry. Direct relay operation, without the use of an amplifier, is possible in most applications because of the 7163's extremely high illumination sensitivity. Other outstanding features are its small size and sturdiness achieved through its compact, space-saving construction. The spectral response of the 7163 covers the approximate range from 3300 to 7400 angstroms. Maximum response occurs at about 5800 angstroms.

RADIOTRON 6032, 6032-A

The Radiotron 6032 is a three-electrode tube of the image-converter type, which, in combination with suitable optical systems, permits the viewing of a scene with infrared radiation. It utilizes a semitransparent photocathode on which the scene to be viewed is imaged by means of an optical objective. The image on the photocathode is focused on the fluorescent screen by electron-optical methods to form a reduced image, which can be viewed with an optical magnifier.

The objective may consist of a Schmidt optical system or a conventional objective lens. The inverted image produced by the optical system on the photocathode is reinverted by the tube to give an observed image which is erect. The 6032 has good response to radiant energy in the infrared region up to about 12000 angstroms, and a minimum resolution of 18 line-pairs per millimetre at the centre of the photocathode. The 6032-A is the same as the 6032 except that it is processed and tested to meet a special performance test.

(Continued on page 200)

effect of a NEGATIVE IMPEDANCE SOURCE on loudspeaker performance

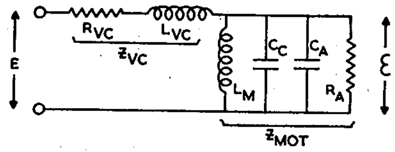
By Richard E. Werner

A direct radiator moving coil loudspeaker driven by an amplifier whose output impedance approaches the negative of the blocked voice-coil impedance can be made to exhibit extended low-frequency response with reduced distortion. The effect of the system is in some ways analogous to a many fold increase in loudspeaker efficiency. In a typical case, neutralization of 70% of the blocked voice-coil impedance completely damps the cone resonance, as well as substantially reducing the nonlinear distortion below resonance. When the amplifier is compensated for the falling radiation resistance at low frequencies, uniform output can be obtained to any arbitrary low frequency, limited only by the ultimate power-handling capability of the amplifier and speaker. In this system, no additional amplifier power is required at frequencies down to the speaker resonance; additional power is required below that point.

INTRODUCTION

Direct radiator, moving-coil loudspeakers are basically inefficient transducers. The influence of the mechanical impedance upon the electrical input impedance is very slight as is typical of most "wide-band" electromechanical transducers. Even the magnitude of a mechanical resonance is often strongly masked by the electrical impedance. Because the electrical impedance of the blocked voice-coil is large compared to the average reflected mechanical impedance, the transfer characteristic of the transducer is largely influenced by the nature of the mechanical impedance.

A commonly used equivalent circuit for a direct radiator, moving-coil loudspeaker is shown in Fig. 1. Useful radiation is assumed to take place from one side of the cone as is the case wherein the loudspeaker is mounted in a totally enclosed box. The reflected radiation resistance, R_a, is inversely proportional to the square of the signal frequency for frequencies below that for which the diameter of the loudspeaker cone is approximately equal to a half-wavelength (the frequency of ultimate radiation resistance). For low frequencies, the air load upon the cone becomes essentially that of a constant mass.



REFLECTED MOTIONAL IMPEDANCES

$L_M = B^2 . L^2 . \frac{C_S \cdot C_B}{C_S + C_B}$

WHERE:
C_S = COMPLIANCE OF CONE SUSPENSION
C_B = COMPLIANCE OF AIR LOAD IN BOX

$C_C = \frac{M_C}{B^2 . L^2}$

WHERE:
M_C = MASS OF CONE AND VOICE COIL

$C_A = \frac{M_A}{B^2 . L^2}$

WHERE:
M_A = MASS OF AIR LOAD ON LOUDSPEAKER

$R_A = \frac{B^2 . L^2}{r_A}$

WHERE:
r_A = RADIATION RESISTANCE PRESENTED TO LOUDSPEAKER

E = INPUT VOLTAGE
$\mathcal{E} = B_{LV}$
WHERE:
B = MAGNETIC FLUX DENSITY
L = LENGTH OF VOICE COIL WIRE
V = VELOCITY OF VOICE COIL MOTION

ELECTRICAL IMPEDANCES

R_{VC} = RESISTANCE OF BLOCKED VOICE COIL
L_{VC} = INDUCTANCE OF BLOCKED VOICE COIL

FRICTIONAL LOSSES ARE ASSUMED NEGLIGIBLE

Fig. 1. Common Equivalent Circuit for a Direct Radiator Moving Coil Loudspeaker.

For acoustic output independent of frequency, it is necessary that the voltage across R_a be inversely proportional to frequency at low frequencies. Therefore, the compliance of the moving system, L_m, is made very large so that its resonance with C_a and C_c occurs at the lowest possible frequency. Unfortunately, for loudspeaker cones and cabinets of convenient size, this resonance appears within the range of musical frequencies; and, by

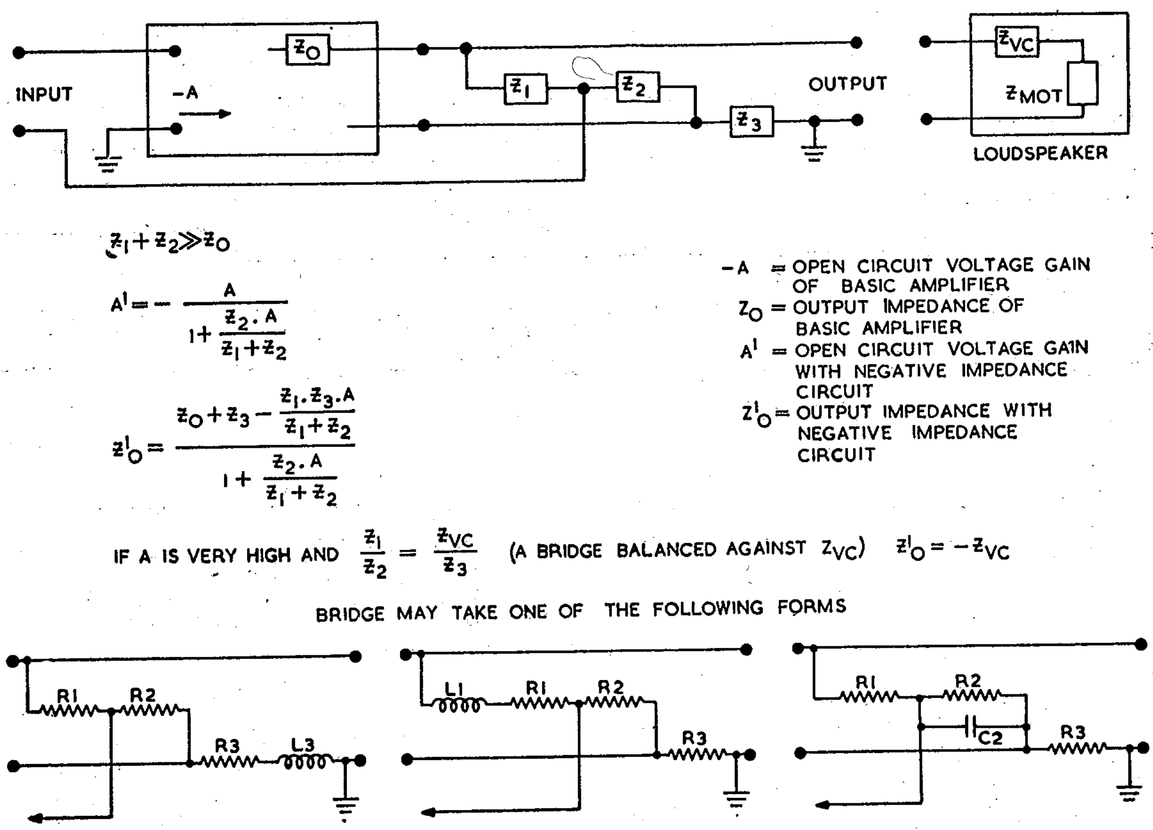


Fig. 2. Basic Negative Impedance Circuit.

virtue of its lack of resistive loading, is insufficiently damped to avoid "ringing" on transient signals. Below the resonant frequency, the loudspeaker cone becomes stiffness-controlled and the acoustic output falls at a rate of 12 db per octave.

In addition to frequency and transient distortions, the direct radiator loudspeaker is subject to considerable nonlinear distortion at low frequencies. Below the resonant frequency, where the motion of the cone is determined principally by the compliance of the system, the nonlinearity of the compliance produces distortion in the radiated sound. There are other factors contributing to nonlinear distortion in a loudspeaker but the nonlinearity of the compliance is the principal offender.

There is an almost limitless number of things which can be done to modify the performance of a loudspeaker. Bass reflex cabinets and semi-horn enclosures can effectively increase the low-frequency output but the effect on transient response and distortion is somewhat controversial. The use of an exceptionally heavy cone and voice-coil, to obtain a low-resonant frequency with a small enclosure, can result in very good performance at low frequencies. This results, however, in a very inefficient system and considerable electrical power is required. The difficulty in obtaining satisfactory high-frequency performance with a heavy moving system also adds to the expense. There is danger, too, of overloading the cone suspension at its low-frequency resonance where the cone excursion may be very great. Another interesting solution is to mount the loudspeaker in a box which has been completely stuffed with acoustic damping material. If the box is fairly large, the Q of the resonance can be lowered sufficiently so that critical damping is achieved with the normal low-output impedance amplifier. This damping is, of course, a power sink and less driving power is required in the vicinity of resonance if the amplifier output impedance itself can provide the total necessary damping.

HIGH EFFICIENCY DIRECT RADIATOR LOUDSPEAKER

If the loudspeaker in Fig. 1 were built with a voice-coil possessing no resistance or inductance, the efficiency would be extremely high, but of more immediate importance, the voice-coil velocity would be an exact replica of the applied voltage. The radiated sound would be free of resonance and devoid of distortion introduced by the non-linear compliance. The low-frequency response would fall at 6 db per octave below the frequency of ultimate radiation resistance and would have to be compensated for.

The high-efficiency loudspeaker can be simulated by inserting a negative impedance in series with the voice-coil to cancel the blocked voice-coil impedance of a normal loudspeaker. It is most convenient to incorporate this negative impedance as the internal output impedance of the driving amplifier. An amplifier so designed for one loudspeaker will function best with loudspeakers of similar blocked voice-coil impedances. Loudspeakers of different motional impedances will, however, perform more alike than when driven by a normal amplifier.

BASIC CIRCUIT

A particularly suitable circuit for obtaining an output impedance composed of a negative resistance and inductance is shown in Fig. 2. In this circuit, positive current feedback and negative voltage feedback are combined in a bridge and fed through a common feedback path through the amplifier. This system avoids complications resulting from gain and phase shift variations which may be encountered if separate feedback paths are employed.

The equations for operation of the circuit indicate that the output impedance is quite independent of the amplifier gain and phase shift when the loop gain is high and the phase shift not severe. With the bridge circuit balanced against the blocked voice-coil impedance, there will always be a net negative feedback at audio frequencies. At the extremes of the frequency spectrum where the reflected motional impedance becomes zero there will be no feedback produced by the circuit. The balanced bridge will, therefore, produce a stable negative output impedance which in no way detracts from the quality of the basic amplifier.

PRACTICAL CONSIDERATIONS

Developing a practical circuit requires consideration of certain factors not yet discussed.

(a) Loop Gain

It is desirable that the loop gain of the circuit be as high as possible. For conventional high quality amplifiers employing considerable feedback, this necessitates the use of additional stages of amplification which may result in stability problems at the frequency extremes when the loudspeaker is disconnected and the feedback voltage is maximum. If oscillation so results, the amplifier may be damaged and such a potential disaster is to be avoided if possible.

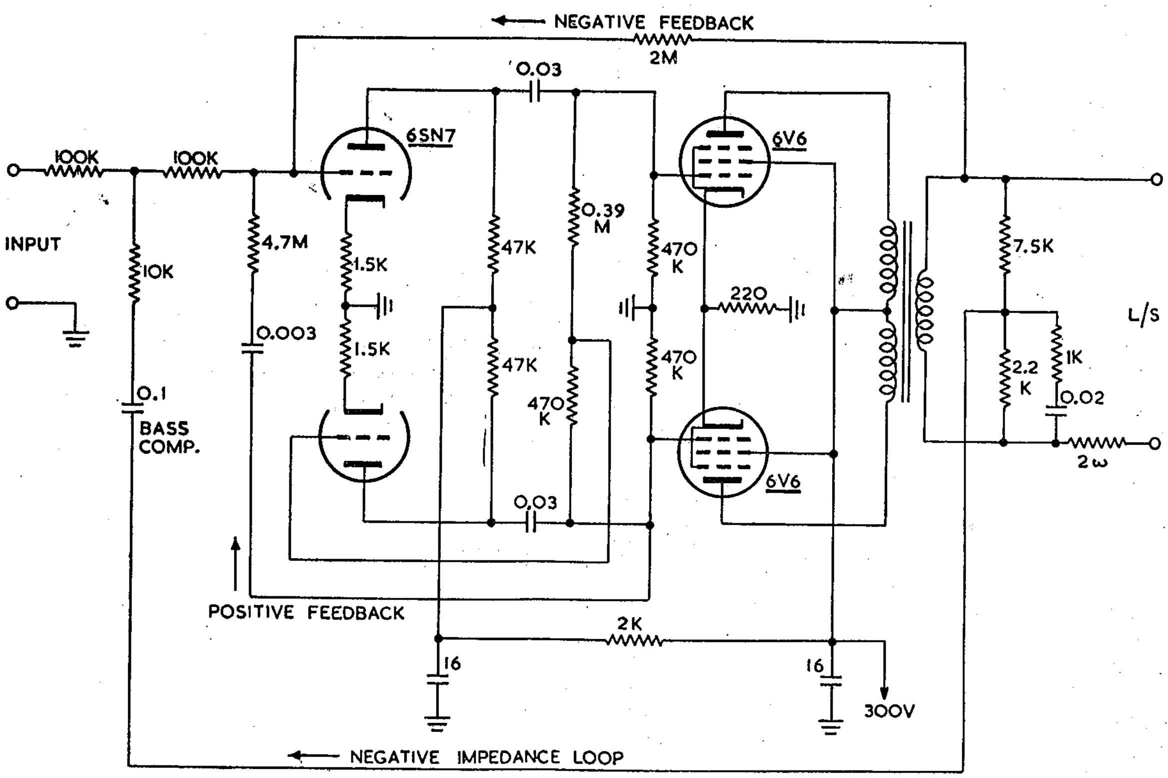


Fig. 3. Practical Negative Output Impedance Amplifier.

Perhaps the simplest solution to this problem is to restrict the circuit to a 2-stage amplifier with little, if any, inherent feedback. The quality of the basic amplifier may be poor compared to a feedback amplifier but its performance with a loudspeaker can actually be superior. Improved results are to be obtained, however, if the basic amplifier is provided with some inherent feedback. The circuit of Fig. 3 is a 2-stage amplifier with a voltage gain of approximately 20 and a total harmonic distortion of only $\frac{1}{4}$% at 40 cps and 10 watts output. This performance has been achieved through the use of positive feedback around the low-level stage, which raises the gain of the main feedback loop essentially to infinity. The feedback factor of 1/20 is slightly more than sufficient to reduce the gain of the circuit to its initial value under loaded conditions. The distortion of the low-level stage is thus reduced slightly and the distortion and output impedance of the final stage are reduced essentially to zero[1]. The low output impedance of this basic amplifier is an advantage in efficiently obtaining a negative output impedance.

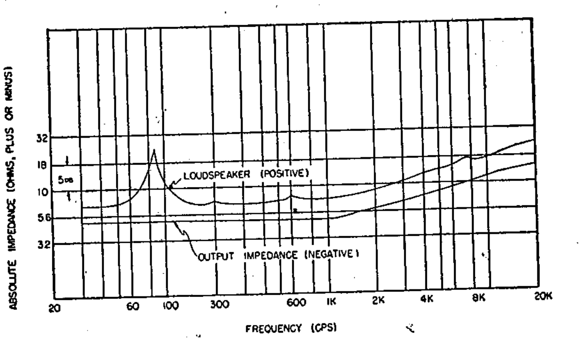


Fig. 4. Impedance of RCA SL-12 Loudspeaker in a 3-cu.-ft. box and Negative Output Impedance of Amplifier.

(b) Voice-Coil Inductance

Another factor which requires consideration in the application of a negative output impedance circuit is the nature of the loudspeaker's blocked voice-coil inductance. This inductance is far from ideal in nature, being influenced by assorted hysteresis and eddy-current losses associated with the mass of iron structure surrounding it. Accurate cancellation of an impure inductance such as this involves considerable complication of the bridge circuit. However, since the actual motion of the voice-coil has little precise bearing upon the radiation of higher frequencies, accurate cancellation of the voice-coil inductance is of doubtful value. Neutralization of a large percentage of

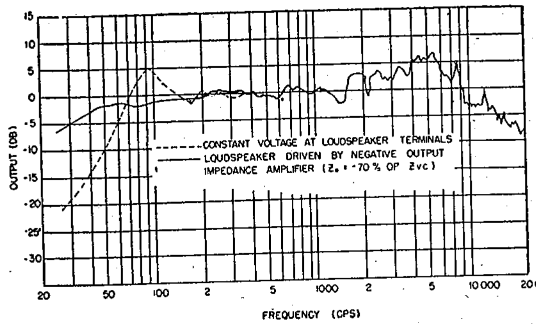


Fig. 5. Response Frequency Characteristics on Centre Line of RCA SL-12 Loudspeaker in 3-cu.-ft. box.

the voice-coil resistance raises the Q of the voice-coil inductance and may result in an undesirable resonance with the mass of the moving system in the mid-audio frequencies unless some reduction of the voice-coil inductance is also provided. The circuit of Fig. 3 combines partial neutralization of inductance and treble boost to obtain an essentially flat high-frequency response into the loudspeaker for which it was designed. The treble boost is inherent in the bridge circuit employed in Fig. 3 because the 0.02 μf capacitor reduces the amount of open circuit feedback at high frequencies resulting in an open circuit response which rises at high frequencies. In practical applications, the amount of negative inductance and treble boost can be chosen to correct for certain general trends in the high-frequency characteristics of the loudspeaker.

(c) Bass Equalization

Proper equalization for the rise in reflected radiation resistance at low frequencies presents a minor problem. In a practical circuit cancelling, say, 90% of the blocked voice-coil impedance, the 10% remaining voice-coil impedance may, for example, be equal to the ultimate reflected radiation resistance of the loudspeaker. In this case, the loudspeaker will be mass-controlled for about an octave below the frequency of ultimate radiation resistance and resistance controlled below

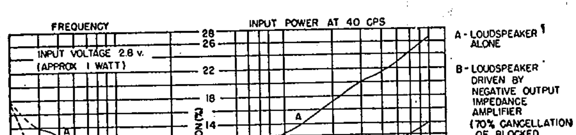


Fig. 6. Total Harmonic Distortion Loudspeaker in 3-cu.-ft. box vs. Frequency and Input Power at 40 cps.

[1] J. M. Miller, Jr., Electronics 23, 106 — 109 (March, 1950)

that point. The bass boost necessary will then properly commence at an octave below the frequency of ultimate radiation resistance. The bass boost is properly positioned when it commences at the frequency where the system ceases to be mass-controlled and becomes resistance- controlled.

Although it is possible in a practical amplifier, of gain less than infinity, to unbalance the bridge circuit so that 100% cancellation of the blocked voice-coil impedance is achieved, such a practice is not likely when production quality control is considered. With less than 100% cancellation, the loudspeaker will eventually become stiffness-controlled at some low frequency and the response will fall at 6 db per octave. If flat response is desired below this frequency, an additional bass-boost circuit may be added as a correction.

The actual frequency at which the reflected radiation resistance begins to rise is determined not only by the physical size of the loudspeaker cone but also upon the placement of the loudspeaker in the listening room. In a very large room, this frequency may vary as much as 2 to 1 in moving the loudspeaker from the centre of a wall to a corner. The average listening room, however, further modifies the radiation impedance as well as the sound pressure — frequency distribution, and correction for these effects are more suitably left for the listener to accomplish with tone controls. Adjustment of the bass equalization for rising reflected radiation resistance appears to be most satisfactory for general applications when corner location is presumed.

In the circuit of Fig. 3, the bass compensation for rising reflected radiation resistance is accomplished in the negative impedance loop, but the circuit parameters are chosen so that there is negligible effect on the efficiency of the negative impedance circuit. The bass boost is effected by frequency-variant loading of the input circuit to the main amplifier.

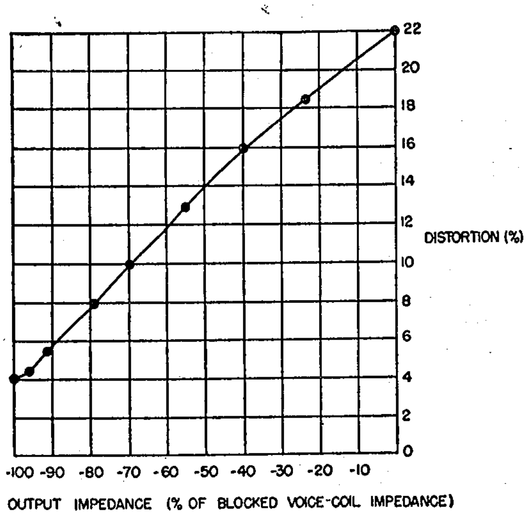


Fig. 7. Total Harmonic Distortion. RCA SL-12 Loudspeaker in 3-cu.-ft. box at 4 watts of 40 cps Input vs. Amplifier Output Impedance.

PERFORMANCE

(a) Loudspeaker in a Large Box

The loudspeaker chosen for these tests is a high quality 12-in. single-cone unit mounted in a totally enclosed 3-cu.-ft. box. The resonant frequency in the box is 89 cps. The impedance-frequency curve is shown in fig. 4 with the output impedance-frequency curve of the amplifier (similar to Fig. 3) which was used for these tests.

1. Frequency Response

The response-frequency characteristic of this loudspeaker is shown in Fig. 5. The negative impedance amplifier is seen to level and extend the low-frequency response.

2. Distortion

The loudspeaker distortion was measured with a ribbon microphone of essentially flat response above 40 cps and a total rms distortion meter. The microphone's sensitivity was low at frequencies below about 30 cps resulting in an apparent noise level comparable to the distortion. Therefore, the distortion measurements below 30 cps are approximate. The distortion characteristics of the loudspeaker are shown in Figs. 6 and 7. In Fig. 6, the distortion is plotted versus frequency at 1 watt and versus power at 40 cps. Measurements were not recorded for powers above 8 watts because the loudspeaker began "ticking" the limits of its maximum excursion. Above 8 watts at 40 cps, the measured distortion did not nearly indicate the increase in listener annoyance due to the "ticking". Driving the loudspeaker with a negative impedance amplifier results in a substantial reduction in low-frequency distortion.

Another possible source of distortion in a loudspeaker is the nonlinearity of the flux density in the voice-coil gap. If distortion due to this cause were of important magnitude, there might be a limit upon the amount of desirable impedance cancellation. Figure 7, however, shows that the loudspeaker distortion continues to decrease as the cancellation is increased to 100%. The values of cancellation above 80% were accomplished in this amplifier by unbalancing the negative impedance bridge, under which condition the amplifier experienced a net positive feedback. Figure 7, therefore, illustrates, in part, the excellent immunity of the circuit to critical adjustment.

3. Transient Response

The response of the loudspeaker to a step-function signal is shown in Fig. 8. To obtain these patterns, a dry cell was connected in series with the loudspeaker and the amplifier in one case, and directly to the loudspeaker in the other case. The battery was shorted to obtain the step function input. The radiated sound was detected by a condenser microphone, amplified, and fed to a long-persistance screen oscilloscope. The transient response of the pickup system was not predetermined and some of the initial transient distortion may be due to the pickup system as well as first-bounce room reflection of the sound wave. Adjusting the amplifier output impedance showed critical damping to occur at about 54% cancellation of the blocked voice-coil impedance.

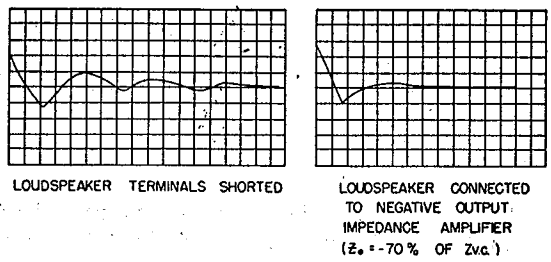


Fig. 8. Response to Step Function Input. RCA SL-12 Loudspeaker in 3-cu.-ft. box.

(b) Loudspeaker in a Small Box

Another loudspeaker of the same type was mounted in a totally enclosed box of ½ cu. ft. The resonance of the speaker in this box, which was just large enough to hold the loudspeaker, occurred at 200 cps. The negative impedance amplifier used to obtain the following frequency and transient responses was an inexpensive 10-watt unit possessing no feedback other than that due to the negative impedance loop. The amplifier is typical of the type used in home and automobile radios. The net negative feedback due to the negative impedance loop is about 6 db at mid-audio frequencies; and the distortion at 100 cps is about 2% at 5 watts. This distortion is of the same order of magnitude as that due to the loudspeaker. For this reason, the distortion measurements for the loudspeaker in the small box were made using the previous amplifier (similar to Fig. 3).

1. Frequency Response

The response-frequency characteristics of the loudspeaker mounted in the small box are shown in Fig. 9. The improvement obtained with the negative impedance source is more pronounced for the small box than for the larger box as one may have anticipated. It is unlikely that any form of acoustical treatment of a ½-cu.-ft. box could produce such a response from a 12-in. loudspeaker.

2. Distortion

The distortion characteristics of the loudspeaker in the small box are shown in Fig. 10. The distortion produced by the loudspeaker is again materially reduced by the use of a negative output impedance amplifier.

3. Transient Response

The response of this system to a step-function input signal is shown in Fig. 11 and is similar to that measured for the loudspeaker in the larger box. In this case, however, the Q of the resonance is higher and critical damping is achieved at about 73% cancellation of the blocked voice-coil impedance.

(c) Subjective Tests

Subjective tests are a necessary assessment of value in a consumer product, particularly an acoustical product. In order to subjectively evaluate the performance of a sound system affecting only the lower frequencies, it is necessary to precondition inexperienced observers so that their attention will be adequately focused on the generally unobserved low-frequency accompaniment. This assumes, of course, that music is chosen for the programme material. The use of selected noises and sound effects may be more effective; but the end use is with voice and music and the system must be so evaluated. About the two systems herein presented: it is difficult to find an adequate music recording to evaluate the performance of the loudspeaker in the 3-cu.-ft. box with an inexperienced audience, but equally difficult to find unsuitable programme material for evaluating the performance of the loudspeaker in the ½-cu.-ft. box.

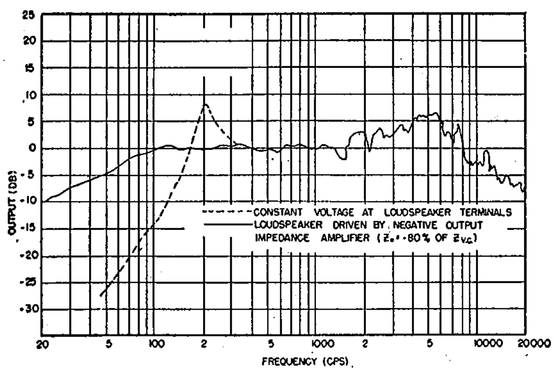


Fig. 9. Response Frequency Characteristic on Centre Line of RCA SL-12 in ½-cu.-ft. box.

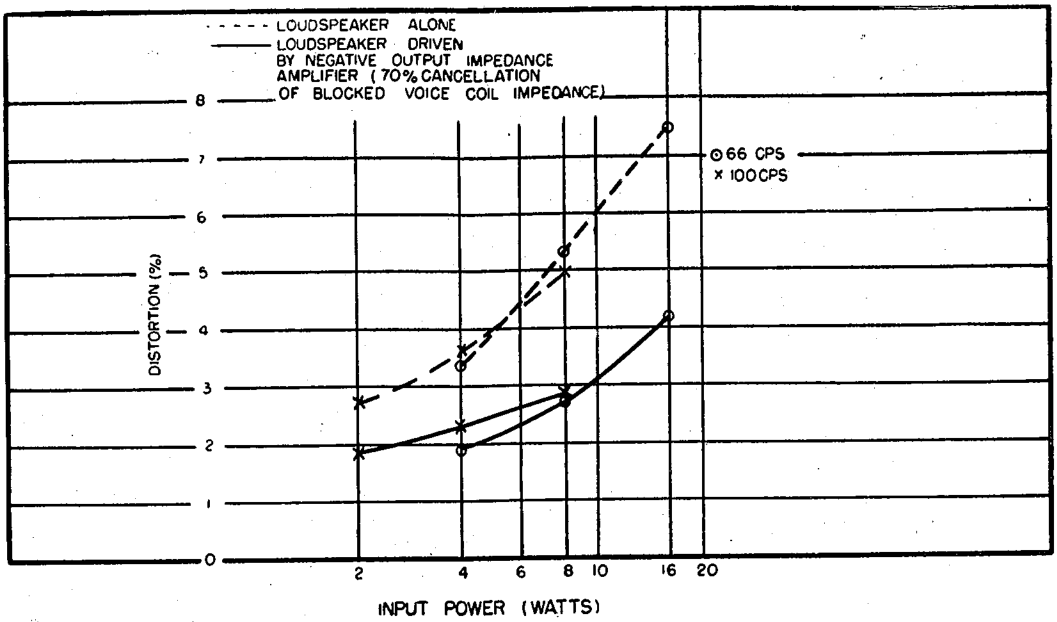
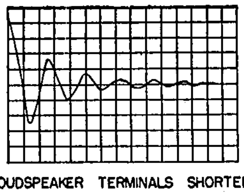


Fig. 10. Total Harmonic Distortion. RCA SL-12 Loudspeaker in ½-cu.-ft. box.

The system was demonstrated before the Delaware Chapter of the Acoustical Society of America on June 7, 1956. A number of loudspeakers were employed including a 4-in. "Drive-In Theatre" loudspeaker in its normal enclosure and a 15-in. "Woofer-tweeter" loudspeaker in a 3-cu.-ft. box. In all instances, an improvement over the normal system was noticed by all members present at the meeting. The effect was most startling in the case of the "Drive-In Theatre" loudspeaker, as would be expected.

The power-handling capability of a sound system is one characteristic which demands subjective listening tests. Because the use of a negative impedance amplifier in no way modifies the efficiency of the loudspeaker no additional power is required in the spectrum above the loudspeaker resonance. The amplifier is required to deliver additional power below the resonance determined by the amount of equalization desired. Subjective tests reveal that a 10-watt amplifier is more than adequate for home use even with the 12-in. loudspeaker mounted in the ½-cu.-ft. box. Musical programme material appears to have a power-frequency distribution such that the 10-watt amplifier overloads at the same volume whether wired normally or with a negative output impedance equalizing to 80 cps.



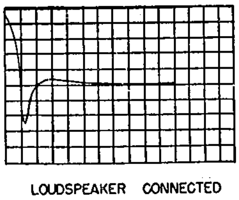


Fig. 11. Response to Step Function Input. RCA SL-12 Loudspeaker in ½-cu.-ft. box (Includes Response of Microphone Preamplifier).

After seven years' subjective evaluation of a negative impedance amplifier, the author has observed that the loudspeaker need not be the limiting factor in the reproduction of low frequency sound. Rather, the quality of the programme material is generally inadequate.

CONCLUSIONS

The results of the foregoing measurements command the following conclusions:

(a) The use of a properly designed negative-output impedance amplifier will greatly extend the low-frequency response, reduce the nonlinear distortion, and eliminate the resonant frequency hangover of a direct-radiator moving-coil loudspeaker.

(b) The improvement in frequency and transient response obtained with this system is most dramatic when the loudspeaker is mounted in a small box wherein the resonant frequency will be higher in the music spectrum.

(c) The music power-frequency spectrum is such that no increae in amplifier power capability wil be required in using this system for most applications.

(d) The improvement in loudspeaker performance obtainable with this system allows the use of less expensive loudspeakers and smaller speaker enclosures in high-quality sound systems.

(e) Because of the poor quality of loudspeakers in comparison with present-day amplifiers, the use of a negative impedance circuit can provide improved performance even with a reduction in quality (and cost) of the amplifier.

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TRANSISTOR RADIO CIRCUIT DESCRIPTION

(Continued from page 189)

life will be somewhat shortened. The no-signal collector current of the Class "B" output transistors should be approximately 1.5 ma to 2.0 ma each.

Some models of transistor radios have negative feedback to reduce distortion. This feedback is accomplished by the addition of only one resistor. In Figure 11 this is R20 (33K). If this resistor were connected to the collector terminal of Q7 instead of Q6, the distortion would be greater than if the resistor were omitted — it must have correct phase relationship.

Figure 12 is a schematic diagram of a typical audio circuit. This circuit uses an audio driver but has only a "single-ended" output. An interstage transformer is used to match more closely the high impedance output of the audio driver to the low impedance input of the output transistor. The volume control is connected to the secondary of the driver transformer and the centre arm is connected so that decreasing the volume control setting tends to present a lower reflected impedance to the collector of the audio driver. This prevents strong signal clipping in the output of the driver stage.

The single output transistor operates Class "A". In this respect it should be noted that the no-signal collector current is approximately 10.7 ma, and has little variation with signal level. Because of this comparatively high no-signal current, the battery life of the 4-transistor set using Class "A" output is shorter than that of a 6-transistor set using Class "B" output.

This article is reprinted with acknowledgements to RCA.

NEW RCA RELEASES

(Continued from page 192)

RADIOTRON 6EM5

Radiotron 6EM5 is a high-perveance beam power valve of the 9-pin miniature type, designed primarily for use as vertical-deflection amplifier in TV receivers having diagonal deflection angles of 110 degrees and operating at ultor voltages up to 20,000 volts. The 6EM5 has a maximum peak positive-pulse plate voltage of 2,200 volts (absolute) and a maximum peak cathode current of 210 milliamperes. These ratings in addition to a maximum plate dissipation of 10 watts enable a single 6EM5 in suitable circuits to provide adequate vertical-deflection for picture tubes used in 110-degree systems.

RADIOTRON 7117

Radiotron 7117 is a multiplier phototube of the 9-stage type, designed for dc automobile-headlight-dimming service. The 7117 has instantaneous response to meet the critical timing requirements of headlight-control service and is capable of providing stable performance over long periods. The spectral response of the 7117 covers the approximate range of 3000 to 6200 angstroms. Maximum response occurs at about 4000 angstroms. When operated with a supply voltage of 1000 volts dc, the 7117 has a median luminous sensitivity of 35 amperes per lumen.