A SIGNAL BIASING OUTPUT TRANSFORMERLESS TRANSISTOR POWER AMPLIFIER

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INTRODUCTION

Present techniques for the design of power amplifiers, whether transistor or vacuum tube, rely upon optimizing performance for pure resistive termination. While this leads to a high degree of compatibility among amplifier specifications and allows quantitative comparison between amplifiers, it does not assure that amplifiers of similar or identical specifications will sound alike when loaded by the same loudspeaker system. It is also axiomatic that subjective excellence with loudspeaker termination requires more costly amplifier construction than less transparent sounding units. By attacking the design of a power amplifier from considerations of the loudspeaker loads that it may be called upon to drive, we shall demonstrate that a good quality amplifier may be constructed from a minimum of components and with an extreme amount of reliability.

THE LOUDSPEAKER LOAD

Let us consider for a moment the nature of a "typical" loudspeaker load. We shall assume that a system will contain at least one electromagnetic driver with a heavy-magnet motor rigidly connected to a driving cone of finite mass. This unit is then loaded in some fashion to the air mass that it is intended to drive. It is a natural consequence of this system that it will possess at least one resonant frequency and will have in the dynamic situation a stored kinetic and/or potential energy dependent upon the past history of the driving signal. In multi-way loudspeaker systems there may be several such drivers connected through reactive frequency-selective crossover networks to the power amplifier and some installations may even contain at least one electrostatic transducer. Such is the load that a power amplifier must drive and it must be admitted that this is anything but a pure resistor. It should be noted then that an actual transducer will differ from a resistor in the ability to store energy and, what is more important, the ability to give this energy back to the amplifier in the form of an electrical signal should the amplifier for any reason evidence a need by no longer maintaining control of transducer voltage. This property of loudspeakers shall then be the basis for our amplifier design.

CONSIDERATIONS FOR MINIMUM COST

In searching for an inexpensive and yet reliable transistor circuit to power the above transducer we find that an emitter follower satisfies both requirements. In order that amplifier construction cost be held to a minimum it is necessary to look at the whole cost including associate driver circuitry, power supply, and heat sinks required. These considerations dictate that the amplifier should take from the power supply only as much power as is required to allow the transducer to be presented the proper signal. Thus a form of Class B or modified class of operation suggests itself. But two active elements together with a means of smoothly transferring signal from one to the other are demanded by the classical Class B amplifier and this is in direct conflict with the requirement of minimum cost. By invoking the energy transfer ability of the loudspeaker, however, we will demonstrate that one power transistor in the emitter follower configuration is capable of presenting a modified Class B mode of operation with the speaker itself acting as the second active element during those brief intervals of time that this is required.

STEADY STATE ANALYSIS

Consider the simplified emitter follower circuit shown in Figure 1. The loudspeaker is replaced for simplicity by the resistor. This is not a new circuit. The additions that are new, however, are the capacitor, diode and potential V. The action of these three new elements is the formation of a peak-clamping circuit to the base of the transistor biasing the base such that the maximum positive excursion remains at a potential of -V. The universal characteristic of the transistor mutual conductance, shown in Figure 2, is such that the emitter potential is a near faithful reproduction of the base. Since source impedance of an emitter follower is the reciprocal of the slope of this mutual conductance characteristic, the loudspeaker may see a Thevenin impedance of an ohm or less throughout the majority of normal emitter current excursions. As the emitter current drops toward zero, however, this source impedance rises very sharply. Another way of stating this is that the base potential controls the emitter potential only so long as a certain minimum current flows. The base loses ability to control the emitter when the emitter current tends toward zero.

This then is the basic steady state action of our amplifier. An emitter follower drives the loudspeaker with the aid of a peak-clamping circuit. The bias of the emitter follower, and consequently the power supply drain of the circuit, is automatically regulated by the signal such that the emitter follower is in a class of continuous conduction and hence continuous control of loudspeaker voltage. We thus have, for the steady state condition, essentially a Class A amplifier and yet we draw power from the supply only as is needed, much like the desired Class B. Figure 3 demonstrates the improvement in dissipation into a resistive load which is afforded by this amplifier.

TRANSIENT ANALYSIS

Some basic questions certainly come to mind while contemplating the inherent distortion that might be introduced into a signal of varying amplitude. It is true that sine wave signals will come through virtually undistorted. And it is true that signals which charge the capacitor would tend to be irrevocably lost to the emitter and constitute distortion if:

1. the emitter were to drive a pure resistor and
2. the diode were perfect.

But it is here that the circuit allows the loudspeaker to enter the picture. Refer to Figure 4 which is more realistic. The loudspeaker has been replaced by a series R L circuit, to represent its energy storage capabilities, and the perfect diode of Figure 1 has been replaced by its counterpart of a threshold potential, series resistance and leakage current. The battery has been given an internal impedance. Now, under the influence of a driving signal, the current through the transistor cannot suddenly be cut off, for the inductor (stored speaker energy) would generate a back emf to maintain continuity of emitter current. Indeed it is possible for the combined effects of diode resistance and loudspeaker inductance to generate a potential considerably more positive than ground and, what is more important, this potential betokens an emitter current, which means that the loudspeaker voltage is actually controlled by the base potential even while both might be more positive than ground. Furthermore, since the diode has resistance, information is not lost to the base even while the capacitor is charging because the base potential is augmented by charging current flowing through the diode resistance. In order to demonstrate the existence of this phenomenon reference is made to Figure 5a. Random noise band-limited from 30 cps to 20 kc/s was injected into a signal biased amplifier. Figure 5a shows a triggered sweep oscillograph of the potential across a typical loudspeaker. The scale factor in time is two microseconds per division and in potential is 0.1 volt per division. The positive deflection is downward and ground is shown by the straight line trace. Observe that not only do positive signal excursions fall 0.1 volt or more below ground but also those signals below ground still convey information instead of appearing as smooth curves. For illustration Figure 5b is to identical scale with Figure 5a but represents the potential across an 8 ohm resistor. Observe now that no signals can possibly get to ground potential and that even those 0.1 volt above ground (negative) do not convey information but rather indicate the complete loss of control of load voltage by the transistor during the charge time of the capacitor. Even more dramatic evidence that the loudspeaker improves performance may be gained from Figure 6a. Here a 10 kc/s square wave of 1.2 volt peak-to-peak was impressed by the amplifier across the loudspeaker. Again ground is shown by the straight line. Figure 6b demonstrates the identical conditions to 6a but with the loudspeaker replaced by the 8 ohm resistor. Across the 8 ohm resistor we see three serious defects:

1. The first is a leading edge overshoot caused by the finite base-emitter capacitance presenting a lower source impedance for the first few microseconds. This is a defect of all emitter followers, but observe how the duration of this overshoot was drastically reduced by the presence of the loudspeaker.

2. A very pronounced slope on the trailing edge of the voltage demonstrates another inherent difficulty with emitter followers; namely, a velocity limited response as current is reduced. Again the loudspeaker back emf was sufficient to minimize this defect.

3. The most positive excursion of the square wave across the resistor is less than that across the loudspeaker. This is a direct consequence of the increased output impedance of the amplifier at low values of current.

For completion of the photographic analysis Figures 7a and 7b show a 20 cycle square wave response across the loudspeaker and the 8 ohm resistor respectively.

COMPLETE AMPLIFIER

A complete signal biased amplifier is illustrated in Figure 8. There are several points which require elaboration since every attempt was made to utilize unique component features. D-2 is a forward biased silicon diode, the forward potential drop of which is utilized for a 0.6 volt "battery". The potential required for this battery was such that with no signal a small voltage would exist across the loudspeaker and allow energy storage to be invoked for signals instantaneously going positive from a quiescent state. Any silicon diode might be used for this location since the fixed potential is a common characteristic. By allowing the collector current of T-2 to flow through the silicon diode we achieve not only the necessary static current, but also a current which tends to nullify the effect of diode impedance under signal drive. D-1 may be any small signal germanium diode. There are two reasons for choosing germanium: first is the previously mentioned low forward potential drop and second is the existence of a leakage current (shown in Figure 4) which, if of sufficient magnitude, will nullify the Ic_0 of T-3 and obviate the need for a protective resistor. By eliminating this resistor we enhance the clamping action and achieve a lower cutoff frequency for a given value of clamping capacitor. The clamping capacitor is fed from an emitter follower of complementary symmetry to T-3. By doing this we achieve a low source impedance for positive going signals which may draw charging currents. For negative going signals the current drain is low enough to avoid the velocity limit characteristic of cutoff emitter followers.

Input resistors establish the base potentials of T-1 and T-2 such that they are entirely in Class A operation at all times. Except for the ratio of these base resistors no other resistor is critical and all might be modified by factors of two or greater without degrading performance. Similarly, since all transistors are in the emitter follower configuration, any type transistor may be inserted for those shown provided they meet the circuit qualifications for symmetry, collector dissipation, and maximum I_{c_o} as determined by the respective base resistors. Any undue temperature rise will not precipitate instability so long as a short circuit is not maintained across the loudspeaker terminals. Rather than degrading performance, a high ambient temperature will cause an increase in static potential which biases the output stage toward a Class A mode of operation. While this increases power supply consumption the amplifier actually becomes more linear. Since T-3, T-4, and T-5 are the only significant consumers of power supply current it is quite fortunate that their collector potentials may be fed from a relatively poorly filtered supply of adequate current capabilities. Any supply ripple on their collectors cannot cause loudspeaker hum so long as there is a few tenths of volts left for the collector to emitter potential of T-3. Power supply ripple cannot be impressed with any measurable magnitude on the base of T-3 by the collector-base leakage since the base of T-3 is constrained at signal frequencies by an emitter follower. It is essential, however, that the negative supply to T-1 and T-2 be filtered. Because the magnitude of this filtered potential need be no greater than the lowest value of the poorly filtered potentials on T-3, T-4, and T-5, it is best obtained by an R C filter section as shown. Beside providing an effective hum-elimination, the resistor capacitor combination allows for a relatively slow rate of charge when power is applied. This slow rate of charge and discharge prevents any large loudspeaker cone displacement at turn-on and turn-off and virtually eliminates an audible turn-on transient even with audio signal applied. If desired, the entire amplifier might be powered from a battery supply for portability. Any supply potential from 1.5 volts to the maximum collector potential rating of the transistors might be used. The existence of power supply impedance for a one-battery operation actually will improve the amplifier operation by providing some measure of negative feedback to T-3. Using the circuit shown, an input impedance of 50 K is realized. Output impedance of the order of an ohm and a voltage gain of unity allows the amplifier to be directly driven from a tuner or preamplifier to comfortable room volume with a moderately efficient speaker. The output power is limited by supply voltage such that the maximum peak-to-peak signal is somewhat less than the available supply voltage.

MEASUREMENT OF PERFORMANCE

No analysis could be complete without some quantitative measure of distortion. Figure 9 is measured intermodulation distortion for a typical signal biased amplifier with no external feedback and a ratio of full-load to no-load power supply current drain of greater than 50. As we would expect, the distortion is lowest into the loudspeaker which, for these measurements, was a James B. Lansing D-130. But here we come face to face with a hard to explain fact. The amplifier when properly constructed unquestionably sounds cleaner on live program material than the intermodulation distortion would predict. This is not a personal feeling but is borne out by the observations of people accustomed to professional equipment. In this sense it is analogous to the listening quality of magnetic tape which often exceeds these distortion figures and yet is far cleaner in audio quality than a feedback power amplifier of lower measured distortion. A possible explanation for a performance which belies measurement might be gained from observing the force displacement curve of a typical loudspeaker such as shown in Figure 10. The displacement being a function of current rather than voltage is constrained to a unilateral motion from rest position. The possible speaker displacement is reduced to half and at first glance is in a more non-linear region of excursion. But it is a nature of the signal biased amplifier that as load current increases the source impedance decreases (refer again to Figure 2). Therefore we find that for a given load impedance current through the load is a non-linear function such as Figure 11. Since the current through the loudspeaker produces the force we find that there exists within the amplifier a first order correction to speaker non-linearity.

One additional unseen benefit that this amplifier provides must be commented upon. Even though the amplifier has a low frequency cutoff as determined by the coupling capacitors used, the output impedance and hence damping factor is held down to dc. This completely eliminates the low frequency "breathing" of speakers commonly found at higher drive levels. The result is a remarkably well defined bass response when compared with some of the finest transformer coupled amplifiers on speakers exhibiting this instability.

It would not be realistic to assume that a signal biased amplifier is so devoid of subjective distortion as to supplant the very finest of amplifiers. While not lost, positive peaks which charge the clamping capacitor must of necessity be reduced in level from the rest of the program. This is distortion, pure and simple. What we have set about to outline was the remarkably stable control exercised over a loudspeaker during these transients and during overdriven clipping signals resulting in a subjective listening quality which does not cause these distorting components to be distressing. All in all the reproduced quality is indeed quite satisfactory when one contemplates the cost of components. When considered in light of the mode of operation a signal biased amplifier cannot be placed in any previously designated catagory such as Class A, B, or Sliding Bias since the loudspeaker load actually enters into the mode of operation. Patent application has been made in the author's name on this mode of operation and the accompanying circuit.

CONCLUSION

A practical output transformerless transistorized power amplifier has been developed which achieves excellent quality at a minimal cost. By utilizing the energy storage capability of a loudspeaker, the amplifier has been shown to exhibit the control of a Class A amplifier with operational efficiencies approaching Class B. The result is a circuit capable of reliable operation over extreme ranges of temperature, supply voltage, and transistor parameters.

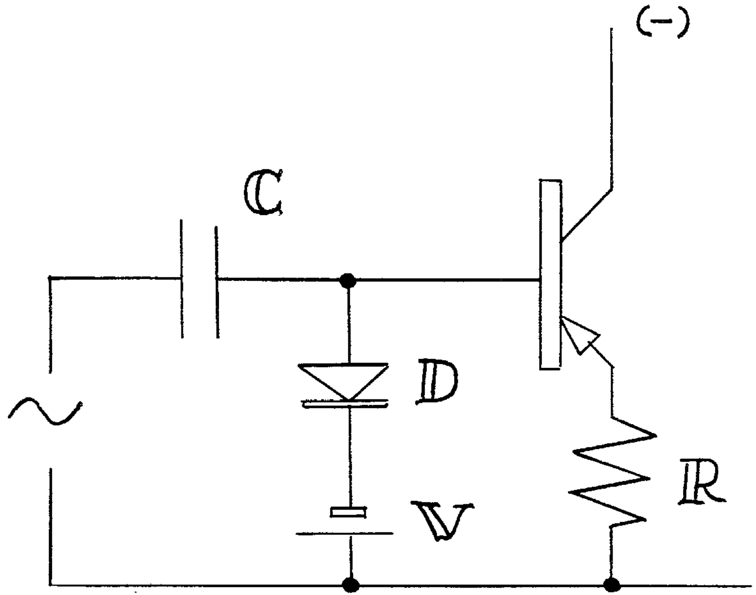


FIG 1. SIMPLIFIED AMPLIFIER

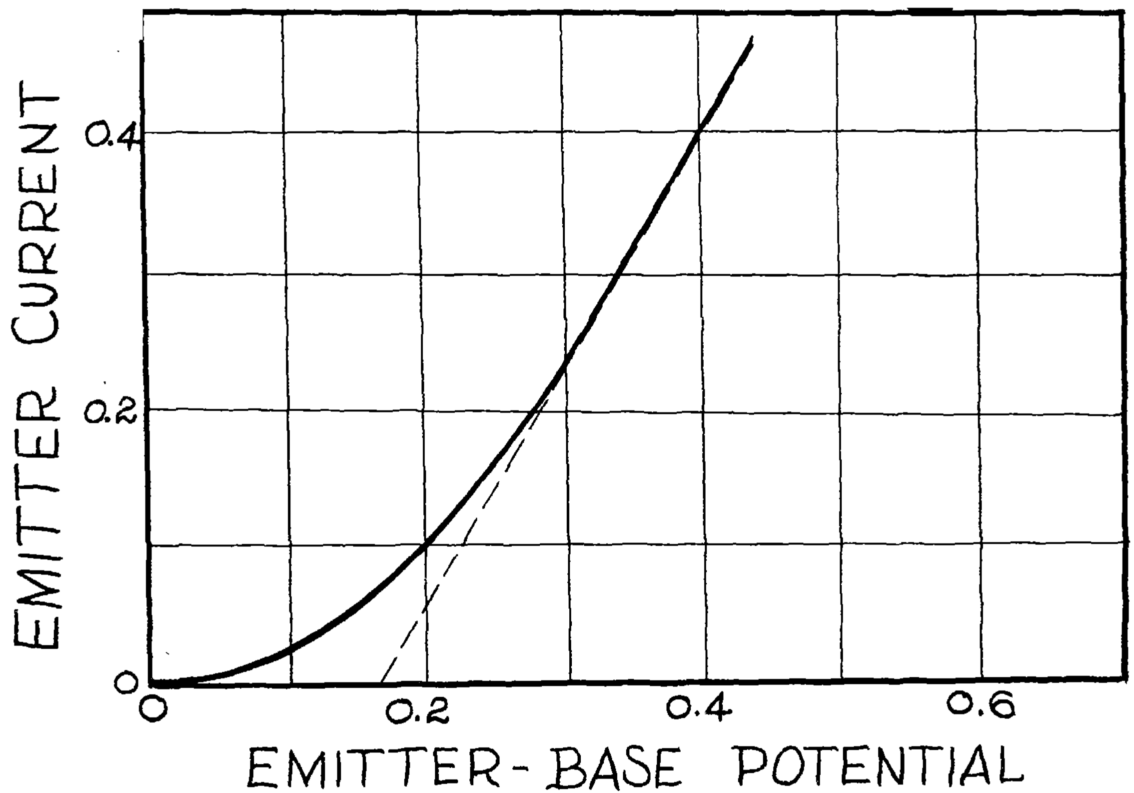


FIG 2. TYPICAL MUTUAL CONDUCTANCE

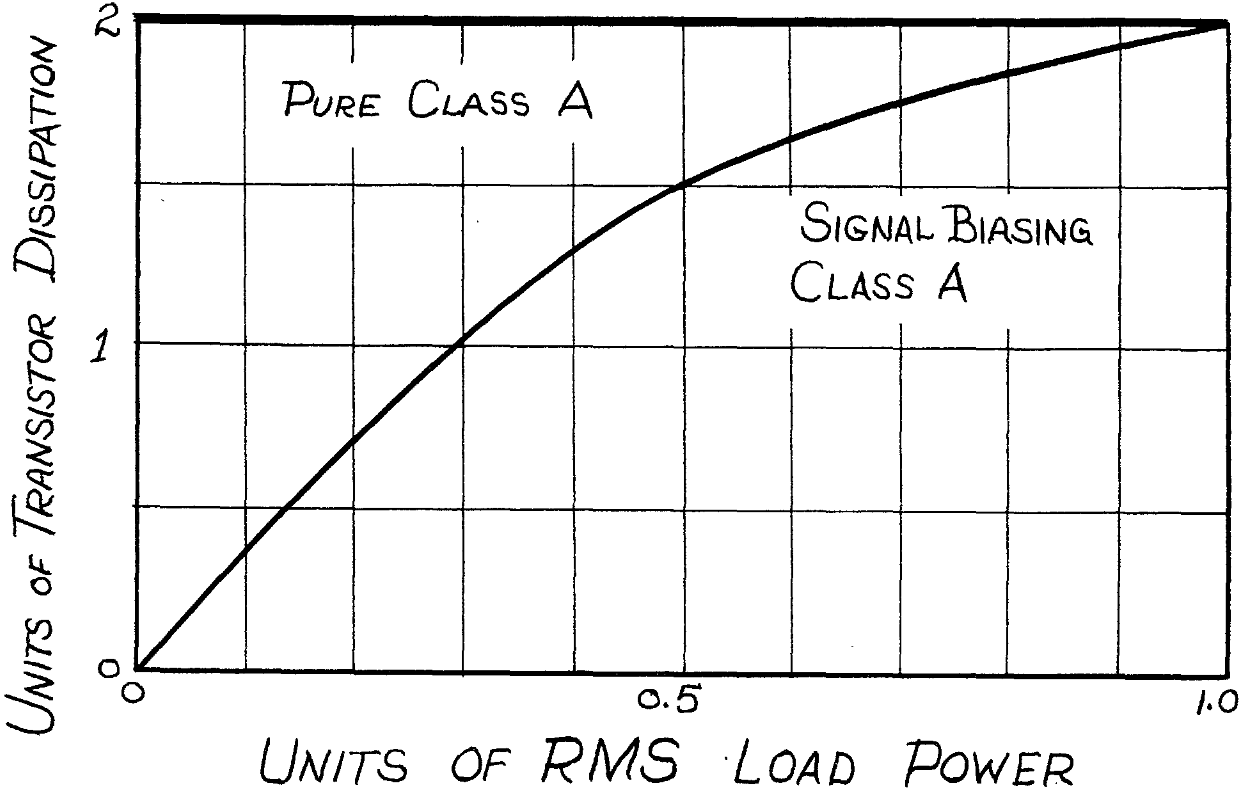


FIG 3. DISSIPATION OF SIGNAL BIASING AMPLIFIER

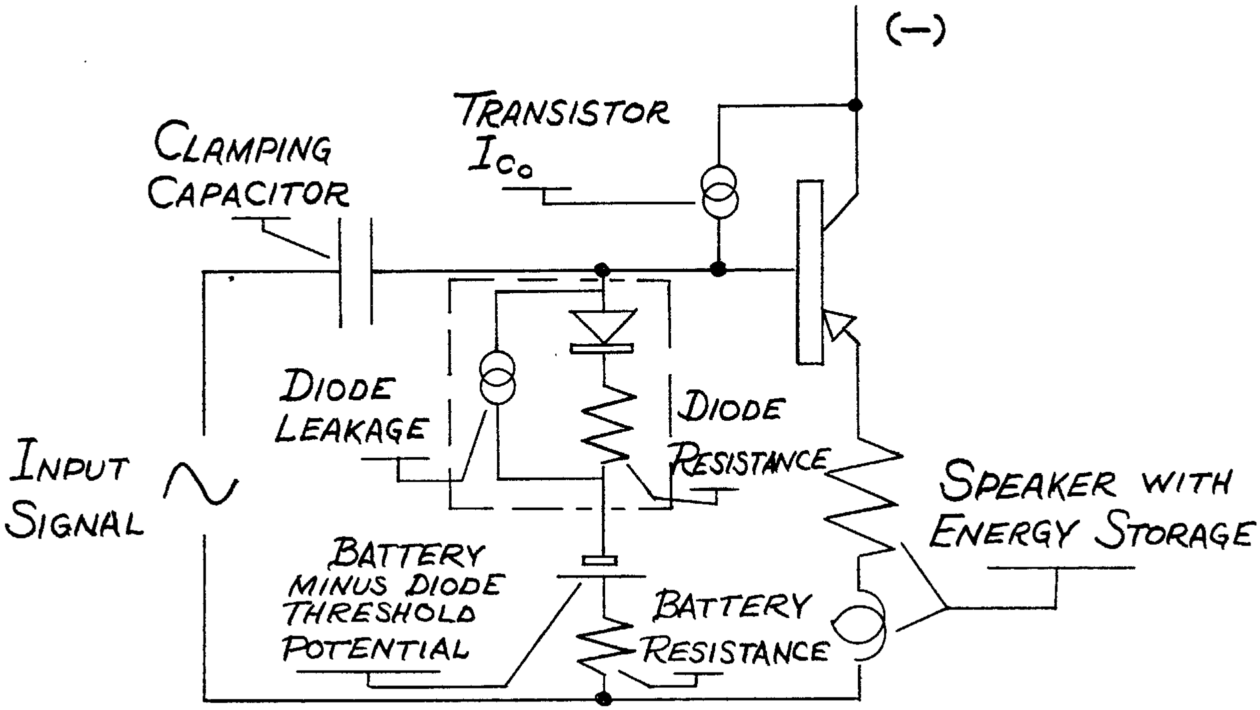
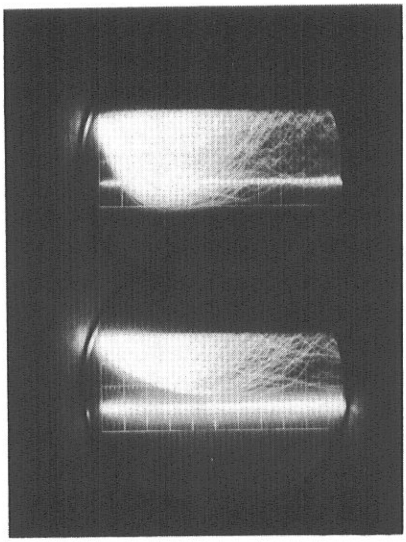
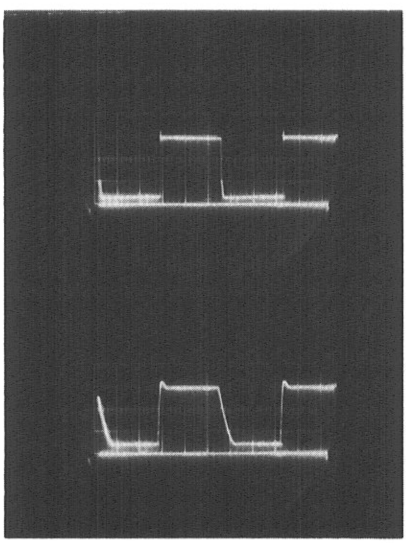


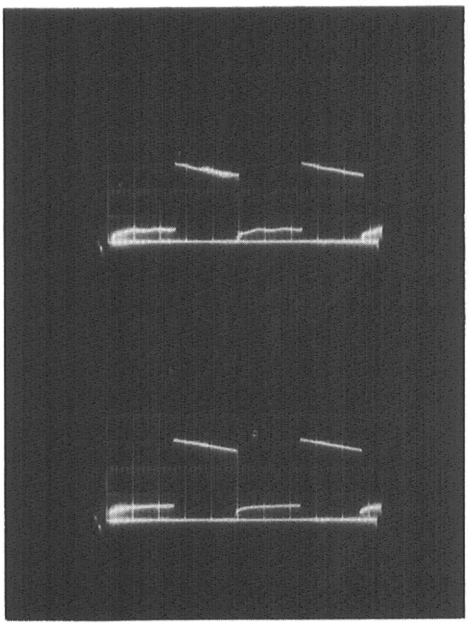
FIG 4. MORE PRECISE AMPLIFIER EQUIVALENT CIRCUIT



RANDOM NOISE
FIG 5a ACROSS SPKR
FIG 5b ACROSS 8Ω



10 KC/S SQUARE WAVE
FIG 6a. ACROSS SPKR
FIG 6b. ACROSS 8Ω



20 CPS SQUARE WAVE

FIG 7a. ACROSS SPKR

FIG 7b. ACROSS 8Ω

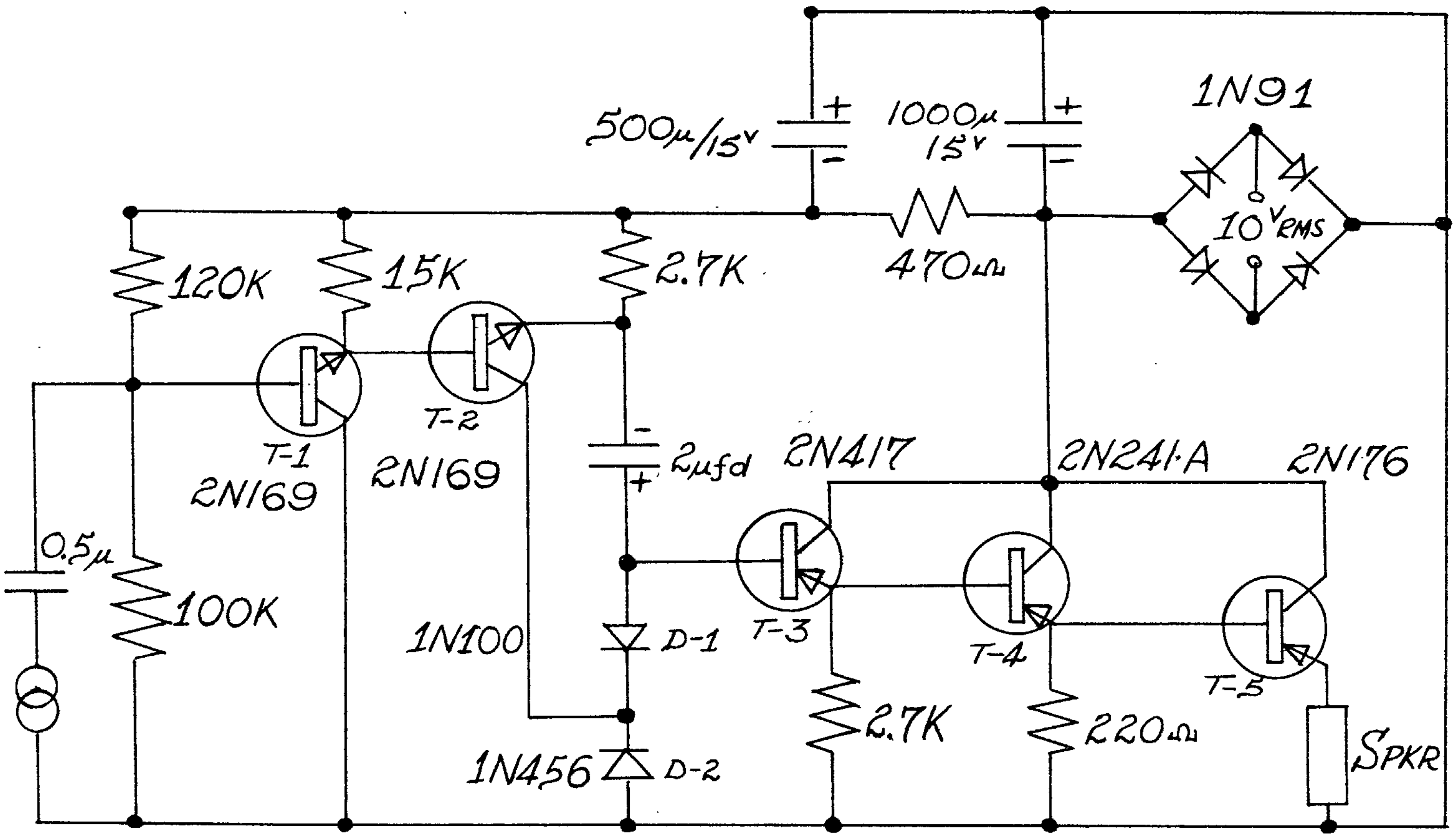


FIG 8. COMPLETE SIGNAL BIASING AMPLIFIER

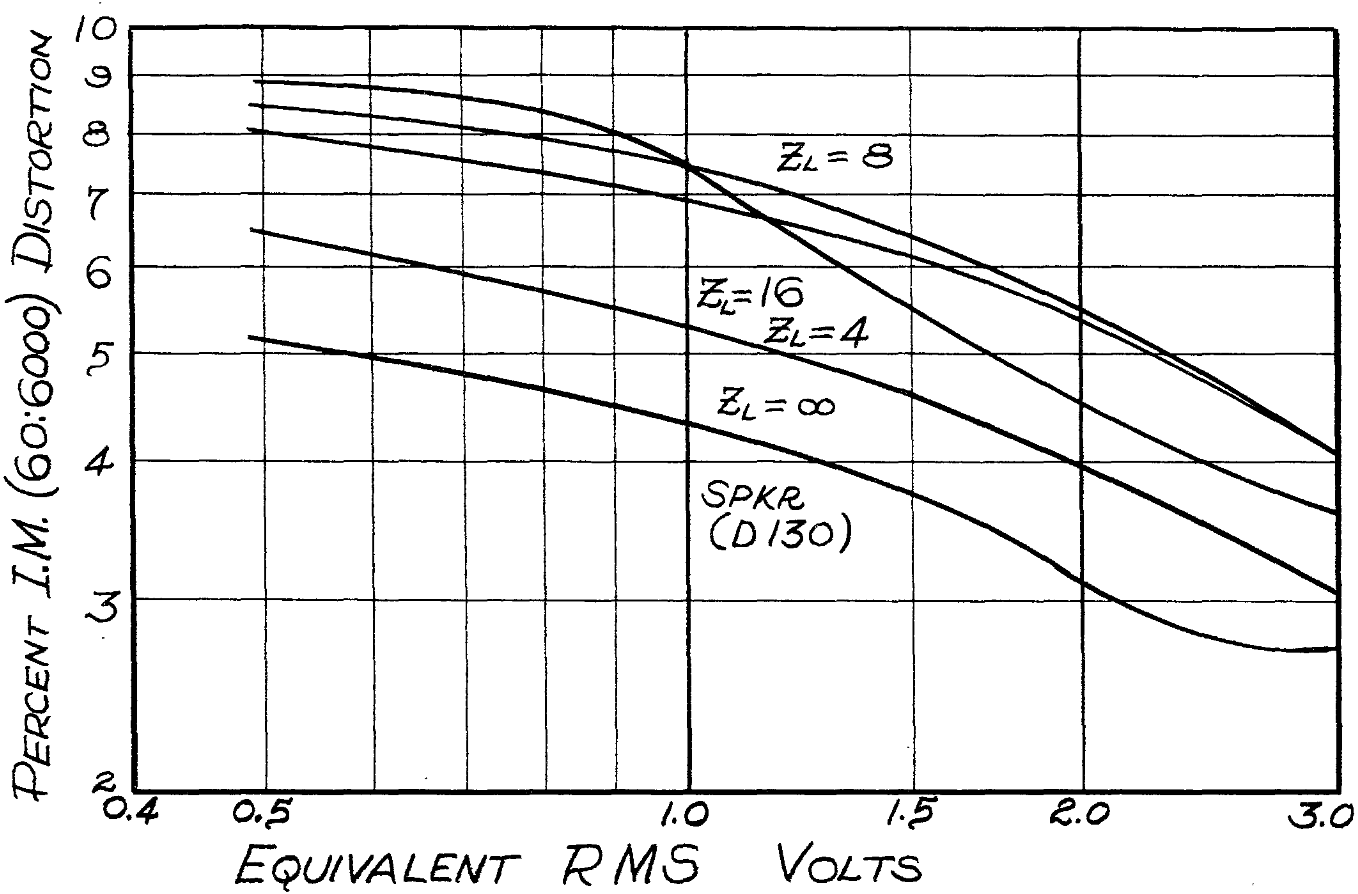


FIG 9. MEASURED INTERMODULATION DISTORTION

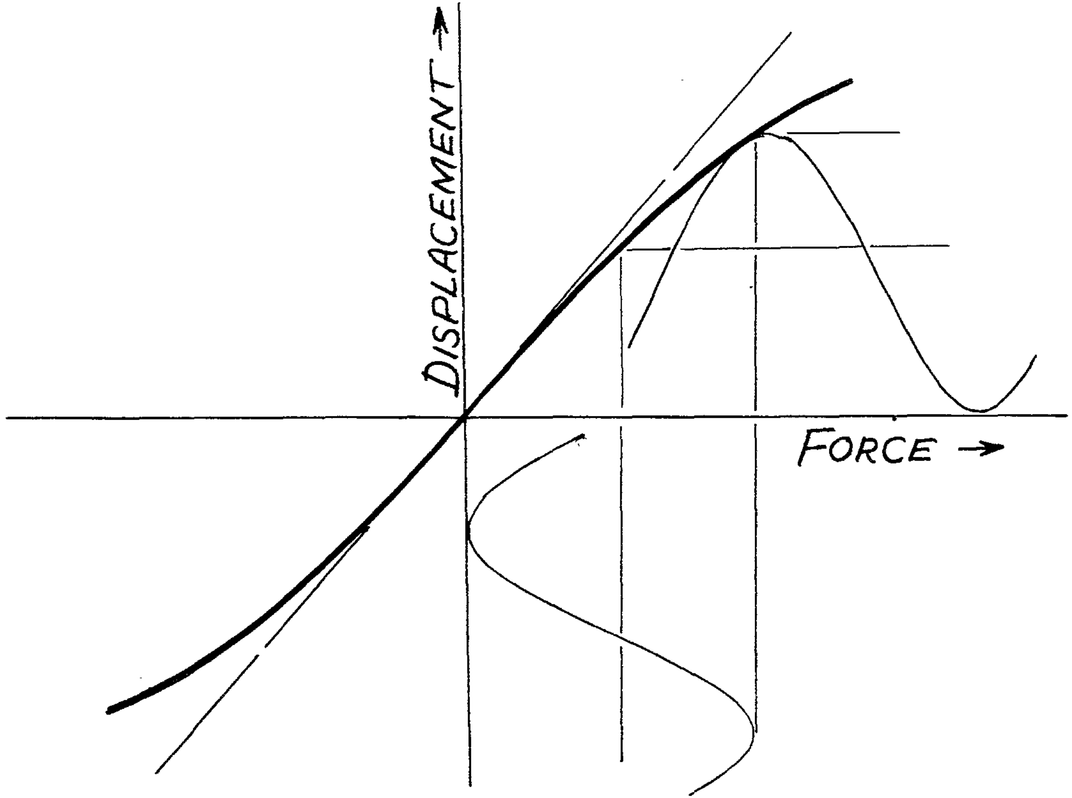


FIG 10. TYPICAL SPEAKER FORCE vs DISPLACEMENT

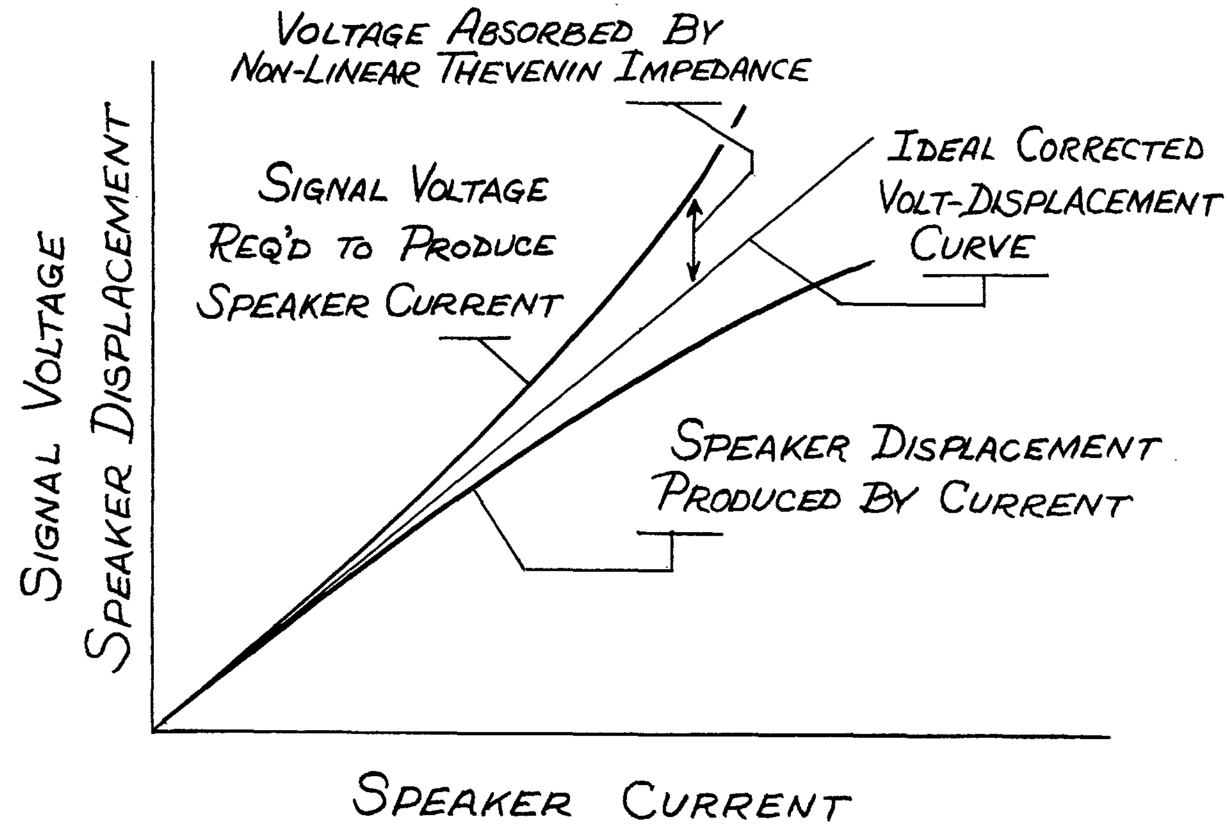


FIG 11. FIRST ORDER CORRECTION TO NON-LINEAR LOUDSPEAKER FORCE~DISPLACEMENT FUNCTION