Audio Amplifiers*

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Summary—**In this paper the design and testing of audio amplifiers is discussed. Attention is also given to the question of comparing the performance of different amplifiers and to the lines along which future investigation should proceed.**

Introduction

IT HAS BEEN assumed frequently that amplifier design is now quite conventional and that the real problems in audio frequency reproduction are associated with loudspeakers and acoustics. However, recent investigation into amplifier design has revealed a series of problems with no direct indication as to how their solution might be obtained. This paper describes a number of these problems and suggests an approach to the solution of some of them.

This paper is limited to a discussion of "main" amplifiers as distinct from preamplifiers since, in general, the most serious design problems in a complete audio frequency reproducing system occur in the main amplifier. Preamplifiers may assume many different forms according to the requirements of each particular application but, by good design, the nonlinear distortion in the preamplifier can be, and should be, less than that of the main amplifier.

It is generally agreed that a good "main" amplifier should possess the following characteristics:

1) Low nonlinear distortion and hence low harmonic distortion and low intermodulation distortion. Anything in the nature of a sharp kink in the linearity characteristic (input voltage vs output voltage) has a particularly distressing effect on the listener—far in excess of that indicated by the usual measurements of percentage distortion—and is therefore to be avoided where good fidelity is desired.
2) Substantially uniform frequency response over the whole audio range.
3) Sufficient maximum power output to handle peak power requirements under anticipated operating conditions over the whole audio range without noticeable distortion.
4) A good "overload" characteristic—that is, the distortion at outputs above the rated maximum power output should not increase at an excessive rate.
5) Sensitivity sufficient to provide the rated maximum power output with an input of not more than 1 or 2 volts.
6) Ability to reproduce any likely forms of transients without serious change in waveform.
7) The amplifier should not add to the information with which it is presented, for example, by overshoot, damped oscillations, etc.
8) Low output resistance—not greater than 20 per cent of the nominal load impedance.
9) Very low hum level.
10) Very low noise level. In most cases the noise contributed by the main amplifier is negligibly small compared with that from the preamplifier.

Amplifier Design Considerations

Output Valves

Effects of Loudspeaker Load: All amplifiers of the types being considered are intended to drive a loudspeaker. A very few are designed for operating one and only one loudspeaker, but the vast majority are intended for use with any one of a wide range of loudspeakers. A loudspeaker presents to the amplifier an impedance which may vary normally by a ratio of 10 to 1 while one world-famous high-fidelity loudspeaker varies by a ratio of 20 to 1. In addition, the loudspeaker impedance is reactive over most of the frequency range, presenting an elliptical loadline to the output tubes.

The effects of these variations, both in impedance and phase angle, are minimized by the use of push-pull Class A triodes, but are serious with pentodes and beam power tetrodes. The effects of a 10 to 1 variation in load impedance for purely resistive loads are shown in Figs. 1 to 3 inclusive. Fig. 1 shows the composite characteristics for a typical pair of push-pull Class A triodes. Fig. 2 shows the same characteristics for a pair of beam power amplifiers. A generally similar effect also occurs with pentodes. It can be seen that the triode characteristics are much more linear than those of the beam power tube. The linearity of the latter's characteristics may be improved if the screens are connected to taps on the plate winding of the output transformer. This arrangement is known as the "ultralinear" amplifier and typical characteristics for a pair of pentodes are shown in Fig. 3.

Pentodes vs Triodes: Pentodes have the following advantages over triodes:

1) They are more sensitive, requiring less input voltage for the same power output.
2) They have greater plate circuit efficiency, even when the screen power input is included.
3) They have good "cushioning" effect when approaching the overload point, and the rise in distortion is gradual.

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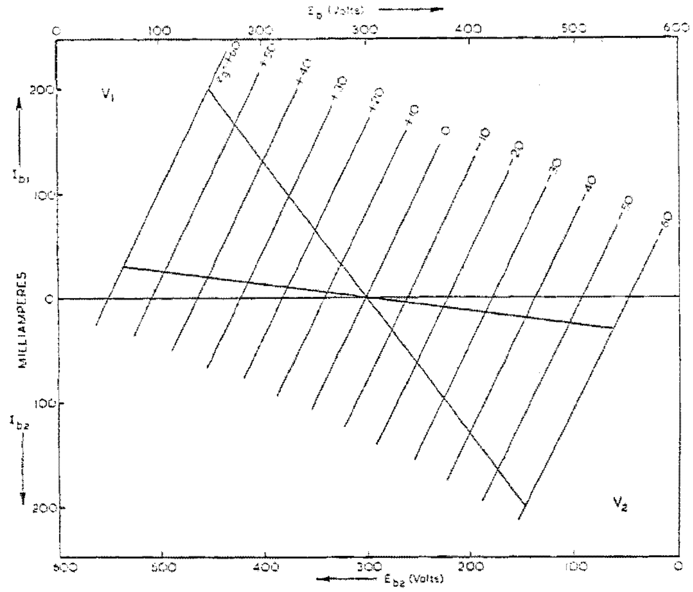

Fig. 1—Composite characteristic curves for two triodes connected as a Class A push-pull amplifier. Load lines for resistance loads of 3000 ohms plate to plate and 30,000 ohms plate to plate are shown.

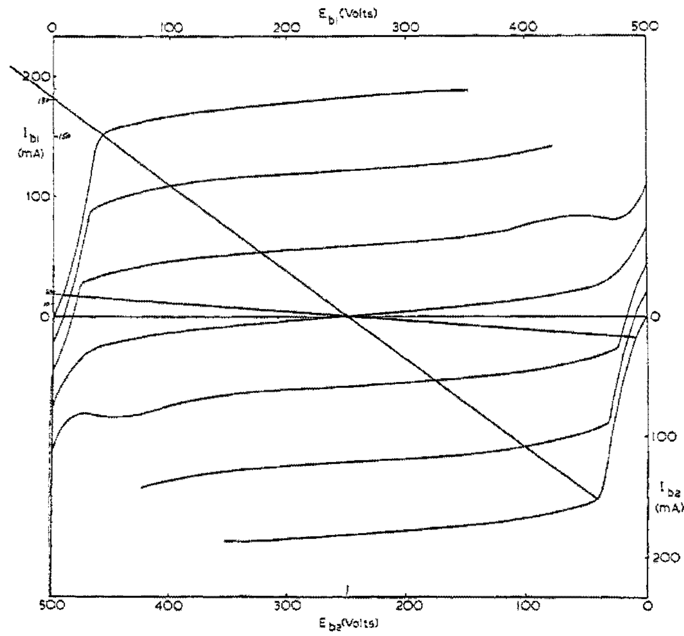

Fig. 2—Composite characteristic curves for two beam tetrodes connected as a Class A push-pull amplifier. Load lines for resistance loads of 5500 ohms plate to plate and 55,000 ohms plate to plate are shown.

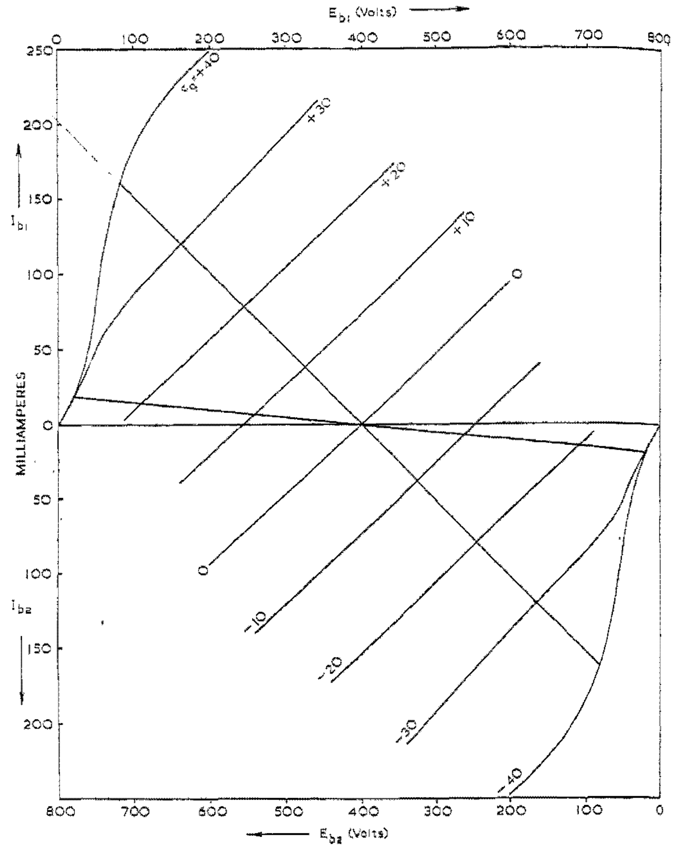

Fig. 3—Composite characteristic curves for two pentodes operated as an "Ultralinear" amplifier. Load lines for resistance loads of 8000 ohms plate to plate and 80,000 ohms plate to plate are shown.

As a result pentodes are very widely used in public address systems and medium fidelity amplifiers.

In high-fidelity amplifiers pentodes have the following disadvantages compared with triodes:

1) They are very sensitive to loudspeaker impedance variations; above and below 400 cps, power output must be reduced to limit distortion to the same as that at 400 cps. Consequently a much larger nominal power output is required with pentodes for comparable performance on a loudspeaker load.
2) In amplifiers of the 15-watt class, it is possible to use pentodes or beam power tetrodes which give the required power output and operate with equal plate and screen voltages. For higher power outputs the usual arrangement is to use a screen voltage lower than the plate voltage, and the regulation of the screen circuit then becomes a problem. Various ways of obtaining good regulation of the screen circuit have been developed but the best methods add appreciably to the total cost.
3) With pentodes the linearity characteristic always shows a gradual curvature over a considerable portion of its length and the slope of the characteristic at maximum rated power output is appreciably less than that at low levels. Consequently the reduction in distortion due to negative feedback at maximum output is considerably less than that at low levels. A greater degree of feedback is therefore required than would be anticipated from the simple theory of feedback. This effect does not occur to any appreciable extent with triodes such as in the Williamson amplifier, which has a substantially straight linearity characteristic even without feedback.

With triodes it is possible to drive quite a distance into the grid current region, with almost perfect linearity so far as the plate characteristics are concerned, provided a sufficiently low impedance driver stage is used. As a result the overloading characteristics are very good. One way of achieving the low impedance driver is by using a push-pull cathode follower although this method is of very little value with pentodes.

It is the author's opinion that, other factors being equal, push-pull triodes are superior to pentodes or beam power tetrodes for the reasons stated. However this optimum performance is obtained at a cost—at least the additional cost of a larger power supply.

Much ingenuity has been shown in the design of amplifiers using pentodes or beam power tetrodes in an attempt to produce results approaching those obtained with triodes. In this field there is strong competition between pentodes operating as pentodes and those operating as so-called "ultralinear" amplifiers. At this stage it is difficult to quote a quantitative comparison, but the "ultralinear" circuit is being adopted widely in both England and the USA for high-fidelity amplifiers. It has the advantage of extreme flexibility of performance merely by moving the tapping point on the output transformer.

Matched Tubes: Certain amplifiers give their specified distortion values only if matched tubes are used but this condition is highly undesirable. The Williamson amplifier requires tubes matched within 5 ma plate current, but the specified distortion of 0.1 per cent is obtained only when the two plate currents are closely matched by using the potentiometer provided. Unfortunately, the tubes tend to drift apart, resulting in increased distortion, and it is unusual for such an amplifier to be checked periodically.

The Leak amplifier Model TL/12 does not require matched tubes nor does it rely on balancing controls, and yet its distortion on a resistive load is less than 0.05 per cent.

Certain other makes of amplifiers also claim to operate within specified distortion limits without requiring matched tubes, but in practice all of them are found to have considerably higher distortion. It seems that the two main features providing for satisfactory operation with unmatched tubes are the design of the output transformer and the use of separate cathode resistors, each separately by-passed.

Feedback

Point from Which the Feedback is Taken: Feedback may be taken from either the primary, the secondary, or a tertiary winding of the output transformer. The primary winding is the simplest and safest to use, since it does not introduce serious problems with instability. Its defects are that it does not reduce distortion caused by the transformer core, and that it results in a high hum level, hence requiring more elaborate filtering. The high hum level is caused largely by feeding back to some earlier stage the full hum voltage on the plates of the output tubes.

The best method for the reduction of distortion is to take the feedback from the secondary winding, but it introduces serious problems in stability usually accompanied by high peaks at low and high frequencies, unless only a small degree of feedback is used. These peaks are due to the large phase shifts which occur in output transformers at very low and very high frequencies, resulting in positive feedback at those frequencies.

The use of a tertiary winding on the output transformer is only slightly inferior to using the secondary of the transformer but it has the advantage that a greater margin of stability is obtained. Its great disadvantage is that a special transformer is required.

Multiple Loops: Most present-day designs have only one main feedback loop—usually from the output to the cathode of an earlier stage. Actually there is a small but useful, subsidiary loop caused by the unby-passed cathode resistor, which not only adds feedback but also helps to improve the stability. It seems that modern design will tend towards the use of multiple loops. One good arrangement comprises two partially-overlapping loops with a third subsidiary loop. This gives the required reduction in distortion with improved stability. The Leak TL/12 amplifier has three loops, both first and second stages having local loops which are enclosed within the main loop over the complete amplifier.

Combined Positive and Negative Feedback: In the usual form, positive feedback is used to increase the gain of the first stage, and over-all negative feedback is used to reduce the distortion. This method seems to have quite a useful future, not only for economical amplifiers, but also in the fairly good fidelity class. It is possible to control the attenuation of the stage employing positive feedback at very low and very high frequencies to improve the stability margin of the whole amplifier.

Transients

In musical reproduction the amplifier is forced to handle a succession of transients of many waveforms, which should be reproduced by the amplifier without distortion of form. In order to achieve this objective the following characteristics are necessary: a rapid rise, small overshoot, very small phase shift, and a slow rate of fall of the "flat top."

The most common method used in the laboratory for determining response to transients is the square wave. All amplifiers give better square-wave response from an electronically regulated plate supply, since an ordinary filter condenser is not capable of maintaining full voltage over the half cycle, especially at low frequencies.

An amplifier required to give good square wave response from 50 to 15,000 cps must possess substantially uniform gain, without peaks, over a very wide frequency range. The precise bandwidth required for a specified performance cannot be stated on present knowledge but all known amplifiers in this class appear to have a substantially uniform response from below 5 cps to about

200 kc. The testing of amplifiers with square wave input voltage is described in the next section.

A sawtooth waveform is approximately equivalent to a square wave of half the frequency, and therefore provides a much more severe test. The Williamson amplifier distorts a 50 cps sawtooth wave, although the reproduction is quite good when the time constant of the intertube coupling is increased four times. Good reproduction of some particular waveforms (*e.g.*, square wave or sawtooth) implies very low phase angle shift, since, for example, the phase angle of the twentieth harmonic is 20 times that of the fundamental. For example, one degree phase shift of the fundamental is equivalent to twenty degrees phase shift of the twentieth harmonic, and the twentieth harmonic of such waveform is quite appreciable.

Stability Margin and Peaks in Gain[1]

It is desirable to have a large stability margin under any possible condition of operation with any value of resistive, inductive, or capacitive source or load impedance—including open and short-circuited conditions. Stability margin may be defined as the increase in feedback, expressed in decibels, which may be applied before sustained oscillations are set up immediately following a large transient input signal. Most feedback amplifiers have their lowest stability margin when their normal load resistance is shunted by a particular value of capacitance and this condition is closely linked with the height of peaks in gain.

The peaks in gain due to feedback which occur at very low and very high frequencies should not, in the author's opinion, rise appreciably above the gain level at 1000 cps. However, some designers (including Williamson) allow one of the peaks to rise up to 6 db above the 1000 cps level on a resistive load, which means that, on a loudspeaker load, one or both peaks may rise considerably higher. When the high-frequency peak is somewhat above the frequency at which the particular loudspeaker changes over from inductive to capacitive impedance, it is likely that the high-frequency peak will be accentuated. Considerable differences are to be expected in the height of the high-frequency peak with various loudspeakers, and it seems preferable for amplifier design purposes to use a normal resistive load shunted by capacitance, the value of the capacitance being determined by trial of successive increments (of the order of ± 20 per cent) to give the maximum peak height. In this way the worst possible condition may be obtained. The effect of any appreciable high-frequency peak, even $+2$ db, on a square wave input is to produce overshoot, followed by damped oscillation commonly known as "ringing" at the frequency of the peak.

In many cases the low-frequency peak is higher than the high-frequency peak, and its effects on performance are more serious. The presence of a low-frequency peak with a level of about $+3$ db or more is usually associated with a fluctuation in level when a high-frequency tone is instantaneously decreased from maximum to say half output voltage. The simplest means of testing for this condition appears to be the application of a 10,000 cps tone switched at 50 cps from maximum to half voltage.

Loudspeaker Damping

A low amplifier output resistance assists considerably in increasing loudspeaker damping in the vicinity of the bass resonance frequency but has no beneficial effect at much higher frequencies. It is possible, by the use of combined positive and negative feedback, to reduce the amplifier output resistance to zero, but this provides very little improvement in the damping compared with a value of the order of 10 per cent of the load impedance. With loudspeakers having high efficiency and high flux density it is possible to reach or even exceed critical damping. With a low efficiency and low flux density loudspeaker there is no hope of reaching critical damping, although even a partial degree of damping is beneficial.

Distortion

It may be asked why it is desirable to have an amplifier with harmonic distortion of the order of 0.1 per cent and whether it is possible to detect aurally such a low level of distortion. Tests by Dr. Olson[2] have shown that approximately 1 per cent total harmonic distortion is the lowest amount perceptible, under the conditions of his tests. These tests were conducted on single triodes and single pentodes and, although no details are given, it is obvious that the test amplifiers did not include any sharp kinks in the linearity characteristics (which only occur in an amplifier when a tube is completely cutoff during part of the cycle), and that there was no incipient instability. Consequently this figure of about 1 per cent is not of general application, and some amplifiers with less than 1 per cent total harmonic distortion are likely to have perceptible distortion.

The total distortion heard by the listener is the sum of the distortion levels in the source, amplifier, and loudspeaker. Therefore any reduction of the distortion in the amplifier is generally desirable and beneficial, although a very small reduction would probably not be noticed by the listener. Another reason for the desirability of a low distortion level is that it gives a comfortable margin for deterioration during the life of the amplifier, particularly in the output stage.

The Testing of Amplifiers

Electrical Testing with Steady Sine Wave Input

This includes all the usual tests for nonlinear distortion, power output, frequency response, output resistance, hum and noise etc. Unfortunately, these tests do not give a true representation of the performance of the

[1] Further experience since the date of submission has shown the importance of avoiding positive feedback at any frequency. This is indicated by a higher response level with feedback than without, at the frequency in question.

[2] H. F. Olson, "Elements of Acoustical Engineering," D. Van Nostrand Co., Inc., New York, N. Y., 2nd ed.; 1947.

amplifier under conditions existing in the reproduction of music. In particular, three features are criticized strongly:

1) The tests for distortion (both total harmonic distortion and intermodulation) do not give values which are truly indicative of the subjective effect on the listener.
2) They are carried out normally with a constant resistive load, and are therefore quite misleading when used to compare different types of output tubes, such as triodes and pentodes.
3) They do not indicate the performance with transient input voltages, this being the usual condition when reproducing music or speech. In the case of Class AB operation, the results obtained with transients depend on the immediate past history of the amplifier, that is, the type of input signal, which has been applied during the preceding moments and its effect on the static grid bias and plate currents.

In addition to these routine tests, it is highly desirable that the gain of any feedback amplifier be measured and plotted, both with and without feedback, over the whole effective frequency band of the amplifier, including both low- and high-frequency peaks. In the case of high-fidelity amplifiers in the Williamson class it is necessary to cover from about 1 cps to 500 kc, and this involves serious problems both with oscillators and measuring equipment.

Electrical Testing with Pulse Type Input Voltages

The most practical laboratory methods for simulating the types of transients existing in speech and music utilize either repetitive pulses or a white noise input. The former includes square wave, sawtooth and other forms and also a high-frequency tone (10,000 to 20,000 cps) which may be pulsed either on/off or pulsed from maximum to reduced-amplitude. A square wave has both a steep rise, which is a transient, and a flat top which is not a transient. Significant features for measurement are the rise time in microseconds (from 10 to 90 per cent of the flat top height, conveniently measured at 10 or 20 kc), the percentage overshoot, the recovery time after the overshoot, and the percentage fall of the flat top measured at some convenient low frequency such as 50 cps. The oscilloscope should give good performance up to 500 kc. It is unfortunate that there is no single figure which can be quoted to indicate the distortion of a square wave.

Although white noise input has been used for the transient testing of both loudspeakers and amplifiers, its peculiar qualities make it a very difficult tool for the amplifier designer to handle, both in use and in interpretation of the results. Consequently no comment is offered at this stage.

Subjective Tests

Subjective tests with a critical listener are vitally important in evaluating the performance of an amplifier particularly in view of our present limited state of knowledge regarding objective electrical tests. It is well known that some amplifiers with less than 1 per cent measured total harmonic distortion at 400 cps give very poor results on a listening test. Some of the many possible causes of this effect include parasitic oscillations over a small portion of the cycle, a sharp kink in the linearity characteristic, and damped oscillations following a sharp transient.

Reliable conclusions from listening tests are obtained only when care is taken with the equipment and the methods used for the test. For comparing two or more main amplifiers with essentially flat frequency response, all the equipment other than the main amplifier (*i.e.*, record player, preamplifier, and loudspeaker) should be common to all tests, and a suitable volume control should be placed before the input terminals of all, or all but the most insensitive, main amplifiers. These volume controls should be adjusted by ear to give identical loudness for all amplifiers under test.

The best available loudspeaker should be used for all the tests; it should have wide frequency range and low distortion, otherwise distortion in the loudspeaker will prevent aural detection of distortion in most amplifiers. The listener should be seated on or near the axis of the loudspeaker, at a distance of 4 to 6 feet. At a greater distance the room characteristics tend to dominate the direct sound. The listener should have in his hands both the volume control and changeover switch. Comparisons should be made at all levels, including overloading, and various types of program material should be used, both speech and music.

It is difficult to arrange a "fair" test when comparing amplifiers having widely different maximum output powers, since in most well-designed amplifiers the distortion decreases as the level is decreased. If the power ratio is two to one, it might be possible to connect two loudspeakers in parallel to the larger amplifier, one being placed in another room. The alternative of using a partially resistive load to absorb the excess power of the larger amplifier is not satisfactory except perhaps with Class A triodes.

Conclusion

No amplifier is perfect, or is claimed to be perfect. As with all other products, amplifier design is a compromise. Exceptionally fine performance may be obtained from a "laboratory" amplifier requiring matched tubes and periodical adjustment, but this is of limited interest.

Unfortunately at the present time there is difficulty in defining suitable tests for amplifiers and so it is extremely difficult to make fair comparisons between different types of amplifiers. Within very limited categories it is possible to make at least an approach towards a fair comparison, for example all pure Class A push-pull triodes may be compared on the basis of total harmonic distortion, performance on square waves, and on pulsed wave-train input voltages. But it is not possible, with our present limited state of knowledge, to compare performance figures of Class A triodes with Class AB triodes, or to compare any type of triodes with pentodes.

This serious lack of knowledge, particularly about the transient performance of amplifiers, is seriously hindering both the design and the comparison of amplifiers. As a result, a long-term laboratory program is now being undertaken on the investigation of amplifier problems, among which are:

1) The operation of resistance-coupled triodes and pentodes following high-impedance stages; also more comprehensive and convenient forms for giving the distortion under a wide range of resistance-coupled operating conditions.
2) Methods of minimizing the distortion rising from the use of output tubes which are not specially matched.
3) A method of measuring nonlinear distortion in such a way as to give a true indication of the effect on a listener.
4) The development of a "dummy" loudspeaker load to be used for the measurement of distortion, power output, and gain vs frequency, which gives results closely approaching those obtained on a loudspeaker load.
5) The investigation of the relationship between the heights of the high- and low-frequency peaks and overshoot and other defects in the reproduction of square wave and pulsed wave-train input voltages, and to put these into the form of numerical values for comparison.

In conclusion, it is the author's hope that the contents of this paper will stimulate discussion on this subject which is of great interest to many people.

Loudspeaker Design and Application*

ARTHUR McLEAN†

Summary—**This paper is concerned with the problems involved in the design of loudspeakers and in the assessment of their performance. The incorporation of design data into speaker applications is also discussed.**

Introduction

MR. STEWART concluded his paper with the theme that the ear is the final arbiter. A wide difference exists between the performance as expressed by present-day instrumentation and that perceived by the ear, because in most cases too many unjustified assumptions and omissions exist in the former. As an example offered to explain this statement a modern amplifier has been analyzed below.

It is known that it handles single-frequncy sine waves down to 5 cps uniformly, yet where Fig. 1(a), opposite, shows a saw-toothed wave of 50 cps applied to the input, the output depicted in Fig. 1(b) is considerably altered. While the amplifier is known to handle single-frequency sine waves uniformly up to 100 kc, its output as depicted by Fig. 2(b) is different from its input shown in Fig. 2(a) when handling white noise of uniform energy per cycle from 40 to 16,000 cps. The conditions under which the tests were conducted are as follows:

1) The oscillograms are photographs of the trace on a high-quality cathode-ray oscillograph.
2) While two beams and their associated amplifiers are available on the equipment, one system only is used in case the two systems do not provide identical performance on complex waves.
3) The amplifier is terminated in a fixed resistor equal to the nominal value of its output impedance.
4) The peak-to-peak values of voltage applied are well below the overload point of the system.
5) The gain of the cro, not the amplifier under test, is adjusted to give a suitable amplitude in each case.

The selection of a saw-toothed wave form as a basis for testing is not due simply to chance. It is the fundamental wave form of speech and animal sounds as well as that of all bowed musical instruments. When a blockage is caused by the vocal cords being closed, air pressure is built up until the cords open and the pressure decreases. To simulate these vocal sounds a steady flow of direct current from a battery is modified in a relaxation oscillator, where the voltages developed depend upon the charging and discharging of a capacitor by a critically-controlled trigger circuit. Thus Fig. 3(a) shows the wave form, using a probe microphone at the vocal cords and Fig. 3(b) depicts the wave form at the lips after the basic saw-toothed wave form is modified by a series of more than the twenty resonant chambers between the larynx and the lips. Thus a suitable synthetic wave form of speech comprises a sawtooth with super-

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