Dynamic Performance of Peak-Limiting Amplifiers*

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Summary—**Dynamic requirements for peak-limiting amplifiers are discussed briefly with respect to such factors as attack time, signal-to-thump ratio, gain-reduction characteristics, and recovery time. There is described a novel measurement technique and apparatus for the visual analysis of the dynamic performance of peak-limiting amplifiers.**

The dynamic characteristics of several typical commercial peak-limiting amplifiers are individually analyzed by a series of cathode-ray oscillograms. These amplifiers exhibit various short-comings of a dynamic nature. As an example of the practical improvement which is obtainable, there is shown the dynamic performance of an experimental peak-limiting amplifier developed by the Columbia Broadcasting System.

I. INTRODUCTION

ALTHOUGH the use of peak-limiting amplifiers in radio broadcasting and recording systems has become very general, the actual dynamic performance of these amplifiers is often a matter of considerable conjecture. Most users know from their own experiences that the action which occurs in a peak-limiting amplifier under actual operating conditions frequently has little correlation to that which is indicated by steady-state sine-wave measurements. Overmodulation "splatter," audible "thump," and "motorboating" are among the more familiar operational defects due to dynamic deficiencies in these amplifiers. Manufacturer's specifications on commercial peak-limiting amplifiers usually include little or no information on dynamic performance, and in the past there has been no available measuring technique or equipment by means of which the user could reliably judge the dynamic merits or defects of a particular amplifier.

It is one object of this paper to describe a measuring technique which provides a means for evaluating the transient characteristics of peak-limiting amplifiers. A second object of this paper is to describe the results of the above measurements as applied to several peak-limiting amplifiers. By way of background, there will first be presented a discussion of some of the dynamic requirements of peak-limiting amplifiers.

II. DYNAMIC REQUIREMENTS FOR PEAK-LIMITING AMPLIFIERS

The essential function of a peak-limiting amplifier[1] is to provide an automatic means of gain control, such that no audio peak amplitude at the input of the amplifier will produce an output level in excess of a predetermined maximum value. A peak-limiting amplifier has an automatically controlled gain characteristic such that its gain is essentially constant for all peak signal amplitudes below the predetermined maximum output value, and is approximately inversely proportional to the input peak signal amplitude for all values in excess of that corresponding to the predetermined maximum output value. A peak-limiting amplifier is usually characterized by a rapid reduction of gain at the onset of a high signal peak, and a relatively slow restoration of gain after the peak has subsided. The time required for gain restoration is usually long, compared to any signal-frequency variations. The minimum time required for gain reduction is commonly known as "attack" time, and the time required for gain restoration as "recovery" time.

Since broadcast program material by nature consists of a series of non-sustained and rapidly recurring signal peaks, a peak-limiting amplifier which does not have a sufficiently short attack time will permit the occasional passage of short signal bursts having amplitudes in excess of that corresponding to 100 per cent modulation of the associated transmitter. If each of the resulting periods of overmodulation does not persist for more than a few milliseconds, it is probable that few listeners will be able to detect the serious wave-form distortion which occurs during these short periods before the gain-reducing action of the peak-limiting amplifier has taken place. However, such occasional bursts of overmodulation in an amplitude-modulated transmitter can set up the well-known and undesirable phenomena of adjacent-channel "splatter." Due to the very steep wave fronts characteristic of many signal peaks, it has been observed experimentally by the Columbia Broadcasting System that the effective attack time of a peak-limiting amplifier should be on the order of 100 microseconds or less, if part or all of these peaks are not to be transmitted at a level in excess of the predetermined maximum.

Most commercial peak-limiting amplifiers on the market today effect the required gain reduction by automatic variation of either a circuit resistance or the signal transconductance of a vacuum tube. In either case, the actual resistance or transconductance variation is usually accompanied by a comparatively large change in the d.c. potential across the variable element. Since this change in d.c. operating values, commonly referred to as "control voltage," occurs at a very rapid rate, it will appear at the output of the amplifier along with the desired signal, unless special means are provided to balance it out. It is, therefore, a fundamental dynamic requirement of a satisfactory peak-limiting amplifier that a high signal-to-control-voltage ratio be maintained at the output terminals throughout each gain-reduction cycle. One audible effect of an insufficient degree of con-

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[1] F. E. Terman, "Radio Engineers' Handbook," McGraw-Hill Book Co., New York, N. Y. 1st edition, 1943, p. 413.

trol-voltage balance is a pronounced and disagreeable "thump" or "click" every time the signal reaches a peak amplitude sufficient to produce limiting.

In some cases the thump component may be so large and the nature of the control circuit such that over-control occurs, i.e., the output signal voltage decreases to a very small value immediately after the onset of an input signal peak. In the most extreme cases of unbalance the thump component may be so heavy as to produce sustained low-frequency oscillations ("motorboating") at the output terminals.

Another requirement of a peak-limiting amplifier is that the slope of the output-signal versus input-signal curve be as close to zero as possible for all input signal levels in excess of that corresponding to the threshold of gain reduction. This is equivalent to saying that the gain of the amplifier should be inversely proportional to the input level for all increases of input level above the threshold point. While this requirement is not in itself a dynamic one, it frequently has a direct bearing on the dynamic stability of the amplifier, since in the majority of commercial peak-limiting amplifiers available today a flat output-level characteristic can be obtained only by an increase of the sensitivity of the signal-control circuit. It is a fundamental relationship[2] that, the greater the sensitivity of the signal control circuits of these amplifiers, the more susceptible the amplifiers are to "thumping" and instability.

The "recovery time" of a peak-limiting amplifier is also an important dynamic characteristic. Optimum recovery time is a combined function of the characteristics of the input signal and the personal preferences of the individual user. The longer the recovery time, the less noticeable is the effect of the automatic gain-reducing action on the dynamic range and balance of the program material. In general, the shorter the recovery time which can be tolerated from a listening standpoint, the higher will be the average signal level at the output terminals. If the recovery time is much shorter than 0.2 second, the gain of the amplifier will change appreciably between successive cycles of low-frequency signal voltages, resulting in severe wave-form distortion. With the exception of a few cases where the amplifier design is such that a change in recovery time also changes the attack time, there are usually no instability problems associated with the recovery-time circuits.

III. DYNAMIC-MEASUREMENT TECHNIQUE

The basic technique of the dynamic measurements to be described consists of suddenly applying a sustained signal of high peak amplitude to the input terminals of the peak-limiting amplifier and analyzing the resulting voltage at the output terminals, from the instant the peak signal is applied until the output voltage reaches a steady-state condition. A sine-wave voltage of a known frequency is perhaps the most significant signal wave form which can be used for such transient analysis, since any distortion of the output voltage due to transient effects is readily detectable. A sinusoidal wave form also provides a convenient time base when measuring the elapsed time from the instant of its application to the amplifier to the time when the output voltage reaches a steady-state condition.

The following dynamic-measurement technique was employed in obtaining the results described in this paper. With reference to Fig. 1, the measurement technique consists of:

1. The application of a sinusoidal signal voltage e of a predetermined frequency f to the input terminals of the peak-limiting amplifier, the amplitude a of the signal voltage being of such a value that the peak-limiting amplifier is on the threshold of gain-reducing action.

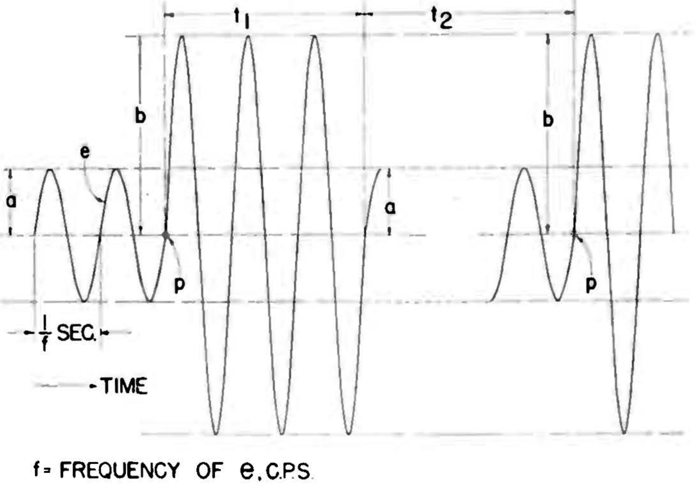

Fig. 1—Wave form applied to input of peak-limiting amplifiers for analysis of dynamic performance. The sine-wave amplitude a i adjusted so that the amplifier is on the verge of gain-reducing action. Amplitude b is any desired higher amplitude. The shift from amplitude a to amplitude b is made at a point p when the sine wave is crossing the axis of zero amplitude.

2. The effectively instantaneous increase of the amplitude of the input signal voltage e to a greater predetermined value b at a time phase when e is crossing the axis of zero amplitude (point p of Fig. 1) in either the positive or negative direction, as desired.
3. The maintenance of amplitude b of the input signal for a predetermined time interval t_1, and at the end of that interval the restoration of the input signal level to amplitude a for a predetermined time t_2.
4. The connection of a cathode-ray oscillograph to the output terminals of the peak-limiting amplifier, and the initiation and synchronization of a linear-time-base sweep voltage in the oscillograph, so as to display visually on the cathode-ray tube a predetermined number of cycles of the output signal voltage immediately before and after the application of signal amplitude b to the input of the amplifier.
5. At the end of time t_2, the repetitive re-application

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[2] W. L. Black and N. C. Norman, "Program-operated level-governing amplifier," PROC. I.R.E., vol. 29, pp. 573–578; November, 1941.

for times t_1 of the increased amplitude b to the input of the peak-limiting amplifier. Time t_2 may or may not bear a fixed periodic relationship to t_1. It is required only that time (t_1+t_2) be an integral multiple of $1/f$, and that the sweep voltage of the oscillograph be so initiated and synchronized that successive traces of the electron beam across the cathode-ray-tube screen are exactly superimposed on one another to produce a stationary visual pattern of the output signal voltage for the predetermined number of cycles before and after the application of the increased amplitude b to the input of the peak-limiting amplifier.

6. The graphical analysis of the amplitude and wave form of the cathode-ray-tube pattern, and comparison of this pattern with the applied input voltage to the peak-limiting amplifier.

In a study of peak-limiting-amplifier performance, the time t_1 of Fig. 1 is an arbitrary value sufficiently long to allow complete gain reduction of the amplifier to take place. For the specific measurements described and illustrated below, the time t_1 was chosen to be approximately 10 milliseconds. It was subsequently found, however, as will be illustrated, that few if any of the current commercial peak-limiting amplifiers examined reach a stable output amplitude within the 10-millisecond observation period under all conditions of operation.

It is usually required in such an investigation that the time t_2 of Fig. 1 be of at least 1 to 3 seconds' duration, since the recovery time of most peak-limiting amplifiers is of this order of magnitude. Therefore, the cathode-ray tube used for viewing the transient phenomena should have a long-persistence type of screen phosphor, so that a visual impression of the transient trace will remain continuously on the screen between cycles of the recurrent transient phenomena.

The phenomena which occur for the first several cycles immediately after the establishment of amplitude b are usually of the greatest interest. By the use of the above-described measurement technique, the gain-reducing action of the amplifier can be observed cycle by cycle of the applied sine-wave signal, and the attack time is measured by counting the number of cycles of a given frequency to the point where no further change of amplitude takes place. Accompanying undesirable effects, such as thump and wave-form distortion, are also shown in as great detail as desired merely by changing the sweep speed of the oscillograph.

An important requirement of this method of transient analysis is that the change from amplitude a to amplitude b of Fig. 1 be made at a time when the applied sine-wave signal is crossing the axis of zero amplitude. If the amplitude change were to be made at any other part of the cycle an irregular wave front would be developed, rendering the transient analysis more difficult of interpretation.

IV. MEASURING EQUIPMENT

A block diagram of the required measuring equipment is shown in Fig. 2. A signal generator A, which may be a standard commercial type of audio oscillator, delivers a sinusoidal voltage of predetermined frequency to an electronic switch and synchronizer unit, B. The electronic switch and synchronizer unit consists of a combination of electronic circuits which provide the signal amplitude changes, phasing, and synchronizing functions required for the visual presentation of the transient phenomena on the cathode-ray oscillograph, C. The electronic switch and synchronizer unit supplies the input terminals of the peak-limiting amplifier under measurement (block D of Fig. 2) with voltage of the wave form shown in Fig. 1. It also supplies a synchronized triggering voltage to the linear-sweep-control circuits of the cathode-ray oscillograph, C. The cathode-ray oscillograph may be a standard commercial unit, providing it is designed for single-sweep, externally triggered operation.

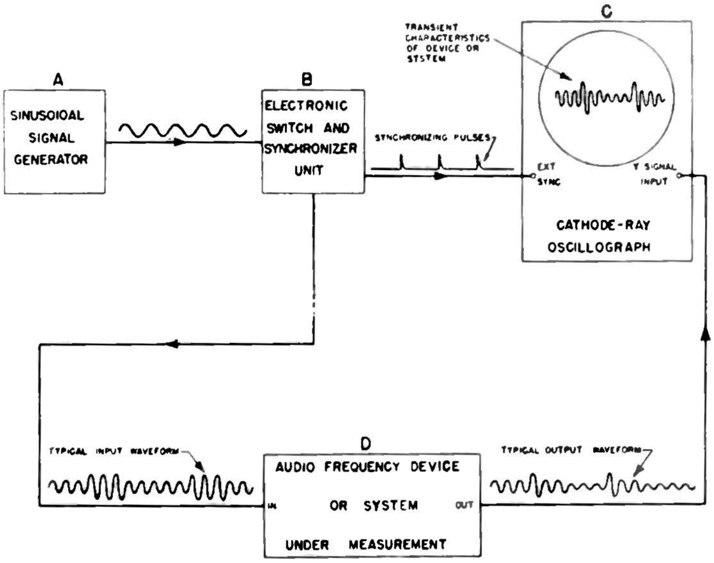

Fig. 2—Block diagram of setup for analyzing dynamic performance of peak-limiting amplifiers.

The transient wave forms displayed on the cathode-ray-tube screen by this method lend themselves readily to photographing. The photographs, which form the basis of discussion for following sections of this paper, were selected from a considerable number taken of peak-limiting-amplifier performance under various operating conditions.

V. OBSERVED DYNAMIC PERFORMANCE OF TYPICAL COMMERCIAL PEAK-LIMITING AMPLIFIERS

The equipment described in the preceding section permits analysis of peak-limiting-amplifier performance at any frequency between 100 and 15,000 c.p.s., and at any desired ratio of peak signal level to threshold signal level (ratio of amplitude b of Fig. 1 to amplitude a). For the sake of brevity, however, results shown in this paper have been confined to two frequencies, 1000 and 10,000 c.p.s., and a single peak-to-threshold signal-amplitude ratio of approximately 18 db. The photographs shown in Fig. 3 are the transient signal wave forms applied successively to the input terminals of each of five different peak-limiting amplifiers. The application of these wave forms to the input terminals result in the output wave forms analyzed individually below for each of the amplifiers. Fig. 3(a) shows the 1000-cycle input wave form, while Fig. 3(b) shows the 10,000-cycle input wave form. These photographs are direct time exposures of the phenomena displayed on the cathode-ray-tube screen. For the purpose of analysis and discussion, reference axes and boundaries have been hand-drawn on many of the photographic prints shown in Figs. 3 through 7.

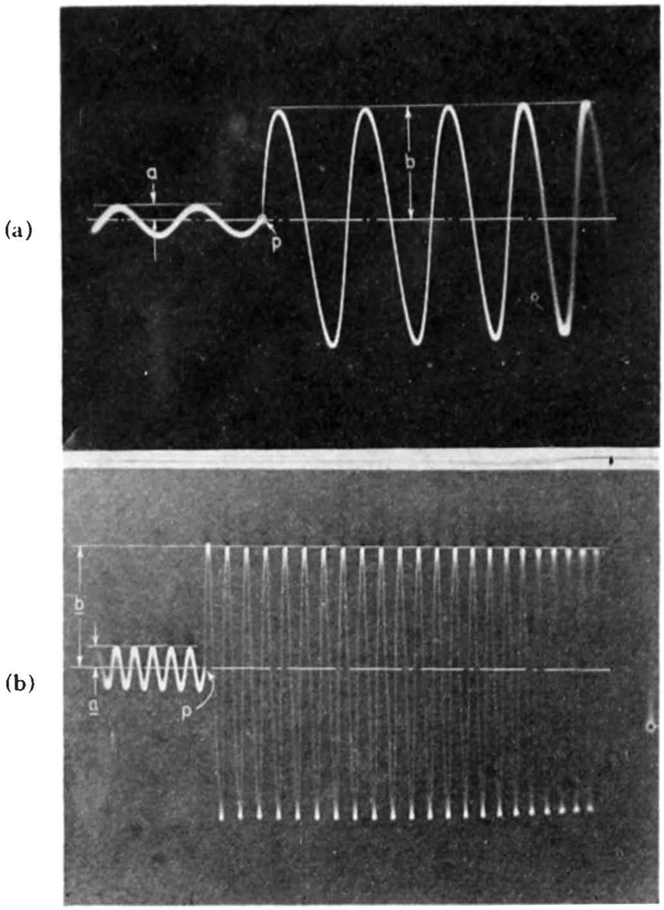

Fig. 3—Photographs of input wave forms applied to peak-limiting-amplifiers for analysis of dynamic performance. These are direct photographs of images appearing on the screen of the cathode-ray oscillograph. Amplitude *a* corresponds to the threshold of gain-reducing action. Amplitude *b* is approximately 18 db greater than *a*. Some second-harmonic distortion of the input wave form is evident, but this does not appreciably affect the results of the transient analyses to follow.
(a) 1000-c.p.s. sine-wave frequency.
(b) 10,000-c.p.s. sine-wave frequency.

The measuring equipment is so adjusted that some two to five cycles immediately preceding the arrival of the transient peak signal are shown for purposes of comparison with the phenomena occurring after the arrival of the transient. As mentioned above, the high-amplitude transient signal (amplitude *b* of Figs. 3(a) and 3(b)) persists for about 10 milliseconds, which is equivalent to 10 cycles of the 1000-c.p.s. signal, and 100 cycles of the 10,000-c.p.s. signal. The sweep speed of the oscillograph is adjusted for good resolution of each individual cycle, which usually results in only the first few cycles immediately after the onset of the peak being displayed on the screen. This is illustrated by Fig. 3(a), where two cycles before and four cycles after the onset of the peak appear on the screen of the cathode-ray tube. Obviously, merely by changing the sweep speed of the oscillograph each cycle can be studied in as great detail as desired, or, if the sweep speed is made sufficiently slow, the action of the peak-limiting amplifier may be observed throughout the entire 10-millisecond period. In general, a relatively fast sweep speed is used when it is desired to study wave-form distortion in detail, and a slower sweep speed is used when the peak envelope is of chief interest. The case of a relatively slow sweep speed is illustrated in Fig. 3(b) for the 10,000-c.p.s. signal, where the first twenty-odd cycles of high-amplitude transient appear on the cathode-ray tube. In this latter case, any cycle-to-cycle peak-amplitude variations would be clearly indicated.

Considerable care was taken in the generation of the applied wave forms of Fig. 3 to insure that no d.c. component of voltage was included in the high-amplitude signal after the points *p*. Close examination of these wave forms will reveal a slight dissymmetry of the positive and negative peak amplitudes due to second-harmonic distortion in the high-amplitude signal. This is not a desirable condition, but one imposed by signal-handling limitations in the electronic switch and synchronizer unit discussed in Section IV. Further development of the latter unit, since these photographs were taken, eliminated this distortion, but it was not considered of sufficient magnitude to affect substantially the results of the present analyses of peak-limiting-amplifier performance.

The response of several commercial peak-limiting amplifiers to the applied wave forms of Fig. 3 will now be analyzed. The sole purpose of these analyses is to describe dynamic phenomena which occur in typical commercial peak-limiting amplifiers; they are intended to be neither a recommendation nor a condemnation of the subject amplifiers.

Peak-Limiting Amplifier 1, Fig. 4

The first two cycles shown at the left of Fig. 4(a) represent an output level corresponding to the threshold of gain reduction, prior to the onset of the sinusoidal signal peak. Study of the wave form beyond the point *p* reveals that the first half-cycle rises to an amplitude *c* approximately 12 db above the threshold amplitude, showing that gain-reducing action has been insufficiently fast to reduce the amplitude of the first half-cycle of the 18-db, 1000-cycle peak by more than approximately 6 db. The amplitude *d* of the second half-cycle is seen to be reduced further, but it is still some 9 db above the peak threshold level *a*. It is evident from Fig. 4(a) that approximately two complete cycles of the 1000-cycle peak are required for effectively complete gain reduction. This can be interpreted to mean that the attack time of this amplifier is 2 milliseconds (the period of two cycles of a 1000-cycle frequency), as indicated by the time t_a on Fig. 4(a). It can be seen from Fig. 4(a) that there has taken place an axial shift of the output voltage during the process of gain reduction, as indicated by the distance g between the axes of the sine wave before and after gain reduction. This is the result of a d.c. component of control voltage which has not been completely balanced out, and represents the "thump" component of this amplifier for the particular peak signal applied. Note that, even though the sine-wave amplitude after gain reduction is apparently no greater than before the arrival of the peak, the axial shift due to thump results in all negative peaks shown on Fig. 4(a) exceeding the negative peak threshold amplitude a by a value of approximately 4 db. Therefore, were amplitude a equivalent to 100 per cent modulation of an associated transmitter, substantial overmodulation would persist for a much longer period than the apparent attack time of 2 milliseconds.

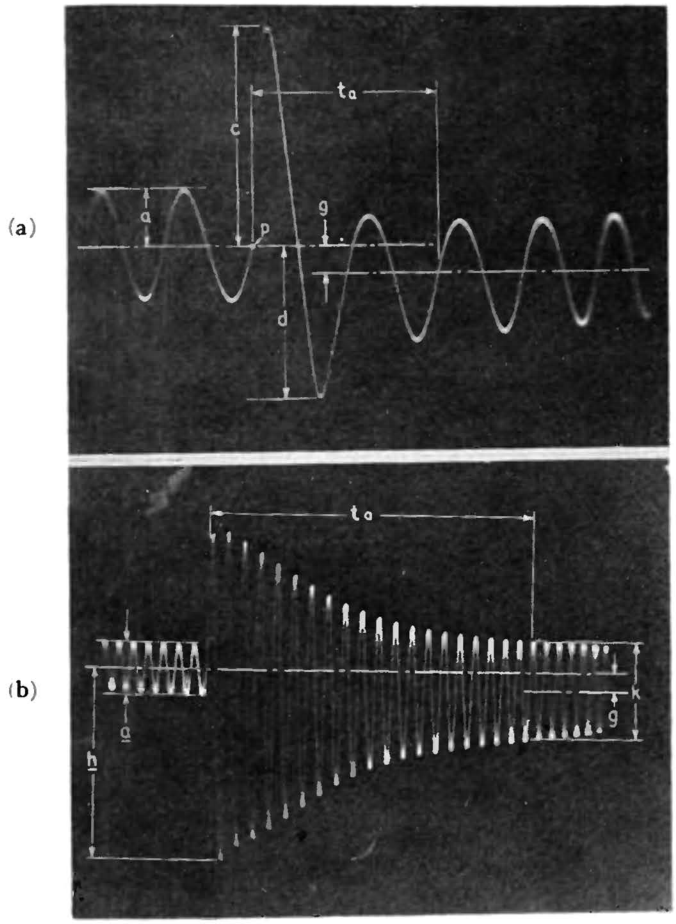

Fig. 4—Peak-limiting amplifier 1. Photographs of output wave forms when input wave forms are as shown in Fig. 3.

(a) 1000 c.p.s. The first cycle after arrival of the higher-amplitude peak at point p overshoots heavily due to slow attack time. Two complete cycles are required before a stable output amplitude is reached, indicating attack time t_a to be approximately 2 milliseconds. A strong thump component g is also shown.

(b) 10,000 c.p.s. The first twenty cycles after arrival of the peak show excessive amplitude, further confirming the attack time t_a to be 2 milliseconds. The steady-state amplitude k is approximately 6 db higher than the threshold amplitude a, indicating deficient high-frequency response in the control-voltage circuit. A thump component g is also indicated.

Since the signal path of no commercial peak-limiting amplifier can pass d.c., the time duration of the thump component indicated by g is a complicated function of the low-frequency response of the amplifier signal- and control-voltage circuits, as well as the feedback-loop gain of the control-voltage circuit. Frequently the amplitude of the thump component decreases in the form of a damped oscillation. This can be considered as an envelope modulation of the signal frequency, and an oscillation frequency on the order of 5 to 10 c.p.s. is common. Therefore, the 2- or 3-millisecond observation period of Fig. 4(a) is too short to indicate any appreciable decrease in the magnitude of the thump amplitude g.

A consideration of the above factors makes it evident that a constant output amplitude may not be reached for an appreciable fraction of a second after the application of a sustained peak signal. The actual time required for an essentially steady-state amplitude to be attained is thus a function of the original magnitude of the thump component and the decay period of the individual amplifier. This low-frequency thump component can very readily have a more disagreeable listening and operational effect on the signal than the short-duration, high-amplitude bursts which pass through the amplifier due to an insufficiently short attack time. For instance, it is not uncommon for the modulator of an amplitude-modulated transmitter using inverse feedback to have a sharply rising, subaudible, low-frequency response, the peak of which may coincide with the thump envelope frequency; in which case the thump is aggravated, and the modulator may be completely disabled for the duration of the thump. In an extreme case there might be developed an oscillation of sufficient amplitude to trip an overload circuit and remove the transmitter from the air.

The magnitude of the thump component in any amplifier varies with the amplitude of the peak which produces gain reduction. Some peak-limiting amplifiers have a so-called thump control which is effective in balancing the thump for any single amplitude of peak signal, but since the gain-reducing circuits seldom exhibit the same degree of balance at any other degree of gain reduction, these thump controls merely permit a compromise adjustment which has the lowest average thump content under normal program conditions.

The thump amplitude g of Fig. 4(a) is by no means of unusual magnitude, as peak-limiting amplifiers go. In fact, it is probably not great enough to be detected solely by a listening test of the audio output of the amplifier. Nor is it likely, either, that the high-amplitude bursts which are shown to occur for the first cycle or two can be detected by a simple listening test.

So far, no detailed tests have been made to correlate the transient effects observed on the oscillograph with the subjective listening effects of these transient phenomena. Preliminary observations, however, indicate that if the amplitude of the thump component, shown by the above sine-wave test, is as great as the threshold signal amplitude (i.e., if amplitude g of Fig. 4(a) is as great as amplitude a), then a listening test with ordinary program material is very likely to disclose a disagreeable "thump" each time heavy gain-reducing action occurs. Perhaps even more significant than the amount of audible thump observed at the output terminals of the amplifier, however, is the possible ill effect the thump component may have on subsequent audio equipment, such as the modulator described above.

Fig. 4(b) shows the effects on amplifier 1 of a peak signal having a frequency of 10,000 c.p.s. Here the 2-millisecond attack time t_a is perhaps more clearly illustrated than in the 1000-c.p.s. case. It is seen that approximately 20 cycles are required after the application of the peak for the output amplitude to approach the more or less constant value k of Fig. 4(b). The first few cycles of the 10,000-c.p.s. peak pass through the amplifier with little or no attenuation.

It is noted that the amplitude k of Fig. 4(b) is about 6 db greater than the amplitude a, a very undesirable condition probably indicating deficient high-frequency response in the control-voltage circuit. This is a deficiency which would also be indicated by steady-state measurements. A thump component g is also present in the 10,000-c.p.s. case.

Peak-Limiting Amplifier 2, Fig. 5

The photographs of Fig. 5 show that amplifier 2 has considerably less amplitude of overshoot than amplifier 1 during the period while gain reduction is taking place. This particular amplifier is designed to produce peak-chopping action at an output amplitude approximately 3 db above the threshold amplitude. The peak-chopping action is independent of automatic gain reduction and, hence, limits the maximum peak amplitude to about 3 db above the threshold value, regardless of how long it takes for complete gain reduction to be effected. Amplitude c of Fig. 5(a) and Fig. 5(b) corresponds to the peak-chopping level of this amplifier, and, were there no gain-reducing action, the output wave form after point p would be flat-topped and of amplitude c. Note, in the 1000-cycle case, Fig. 5(a), that a substantial part of the first half-cycle remains at or near the peak-chopping level, before sufficient gain reduction has occurred to reduce the output amplitude below this value. Fig. 5(b) shows that the output level remains near the peak-chopping value for about the first three cycles of a 10,000-cycle peak.

It may be noted from Fig. 5(a) that considerable wave-form distortion is evident near the peaks of at least the first four complete cycles after the arrival of the 1000-cycle peak. This indicates that gain-reducing action is still going on, even though the peak amplitude reaches a relatively stable value d after the first cycle. If the photograph of Fig. 5(b) were expanded on a faster sweep, considerable wave-form distortion would also be observable over the first 30 or 40 cycles after the arrival of the 10,000-cycle peak. From Fig. 5(b) it is seen that approximately six cycles are required for the output amplitude to reach its stable value d, which indicates that the attack time of amplifier 2 is approximately 0.6 millisecond. In view of the fact that considerable wave-form distortion persists for a much longer period, however, this factor should probably be taken into account. If the attack time of amplifier 2 is based upon the time required for the output wave form to become essentially sinusoidal, the value would be on the order of 4 milliseconds, instead of 0.6 millisecond.

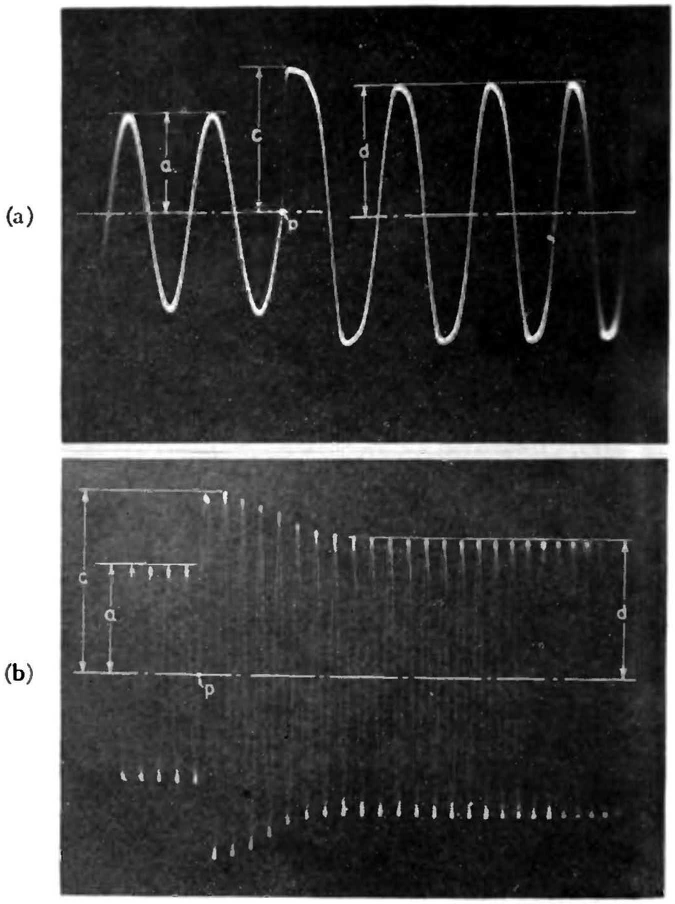

Fig. 5—Peak-limiting amplifier 2. Photographs of output wave forms when input wave forms are as shown in Fig. 3.

(a) 1000 c.p.s. This amplifier includes peak-chopping action for all input peaks more than approximately 3 db above limiting threshold level. The first half-cycle after arrival of the peak reaches the peak-chopping amplitude c. The next several half-cycles, while of reduced amplitude, show considerable distortion on peaks. The thump component is low.

(b) 10,000 c.p.s. The first two or three cycles remain at peak-chopping amplitude c. Approximately six cycles are required for full gain reduction, making the attack time approximately 0.6 millisecond.

Amplifier 2 appears to have a low thump component, is indicated by very little axial shift of the wave form before and after gain reduction. This particular amplifier is provided with a "thump" control, and optimum adjustment of this control was made before the photographs of Figs. 5(a) and 5(b) were taken. However, as noted in the discussion of amplifier 1, the thump control insures a low thump component for only one particular amplitude of peak signal; for some lower or higher amplitude of peak, amplifier 2 might exhibit appreciable thumps.

Peak-Limiting Amplifier 3, Fig. 6

As evidenced in Fig. 6, this amplifier exhibits a heavy thump component. The thump effect of amplifier 3 is great enough to be definitely audible on a listening test with ordinary program material. It is observable from Fig. 6(a) that the initial thump (amplitude *c*) is almost twice the peak threshold amplitude *a*. Note that the zero-signal axis of Fig. 6(a) after the application of the 1000-cycle peak has a definite upward slope to it. This indicates that amplifier 3 has a more rapid thump-decay period than was exhibited by amplifier 1.

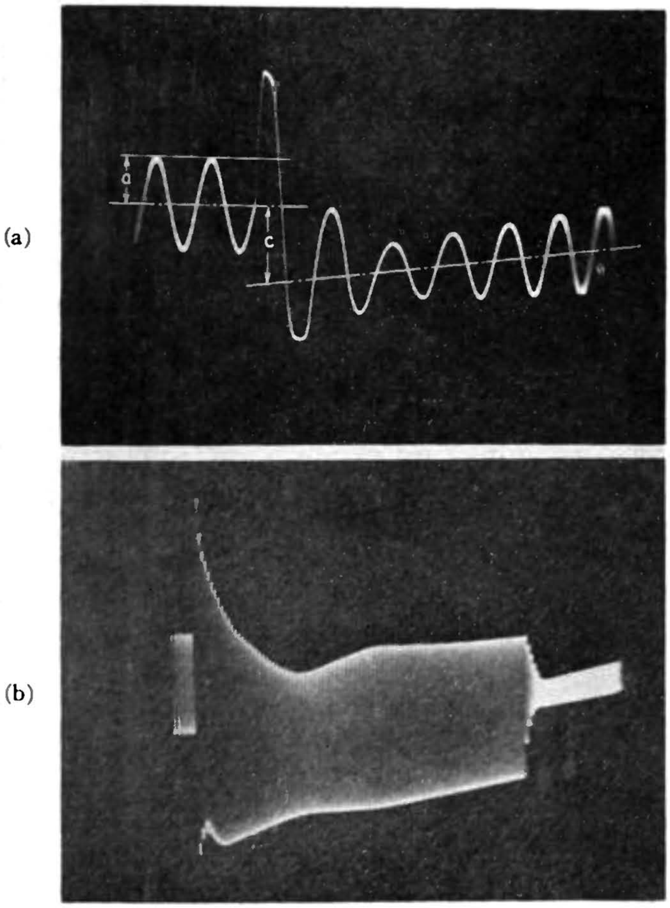

Fig. 6—Peak-limiting amplifier 3. Photographs of output wave forms when input wave forms are as shown in Fig. 3.
(a) 1000 c.p.s. Extremely heavy thump component *c* greater than peak threshold amplitude *a* is shown. The amplitude of the first cycle after arrival of the peak appears to be limited only by the overload characteristics of the amplifier. The fourth half-cycle and several successive half-cycles show severe over-control wherein the amplitude is *less* than the threshold value *a*.
(b) 10,000 c.p.s. Somewhat slower sweep speed was employed for this photograph, so that the entire 10-millisecond period of duration of the peak is visible. No stable output amplitude has been reached during the 10-millisecond interval, so it is not possible to specify with meaning the attack time of this amplifier.

Fig. 6(a) illustrates an effect discussed in Section II of this paper, namely, over-control, or excessive gain reduction. It can be observed that the fourth half-cycle has an amplitude (as also have the next several cycles thereafter) *less* than the threshold amplitude *a*. This is a direct result of too heavy a thump component, and the thump voltage is rectified along with the signal voltage, producing excessive control voltage in the gain-reducing circuit.

Fig. 6(b) shows the 10,000-cycle output when the wave form of Fig. 3(b) is applied to the input. This photograph differs slightly from the 10,000-cycle photographs of Figs. 3, 4, and 5 in that a slower sweep speed has been employed. In this photograph the entire 10-millisecond period of duration of the peak is visible. So close are the individual cycles under this condition that the resulting picture is essentially an envelope of the output peak amplitudes. It is difficult to offer a rational explanation for the shape of this 10,000-cycle envelope, since it is such a complicated function of the transient characteristic of the amplifier circuits.

At the end of the 10-millisecond peak, the output voltage of the amplifier is seen to be less than that immediately preceding the onset of the peak, the difference between the two amplitudes being a measure of the gain reduction that has taken place in the amplifier.

Due to the severe thump components of amplifier 3, it is difficult to specify definitely its attack time. For instance, although Fig. 6(a) indicates that maximum gain reduction occurs about 2 milliseconds after the application of the peak, the negative peak amplitude at that point is still more than 6 db greater than the threshold amplitude *a*, due to the magnitude of the thump. Nor has a stable output amplitude been reached within the 10-millisecond period of duration of the peak.

VI. CBS EXPERIMENTAL AMPLIFIER

In one or several ways it has been observed that each of the peak-limiting amplifiers analyzed in Section V leaves considerable room for improvement. The Columbia Broadcasting System recently developed a unit which has outstanding dynamic-performance characteristics. The dynamic performance of this experimental amplifier is shown in Fig. 7.

The CBS amplifier has a maximum control range of 14 db; therefore, the analyses of Fig. 7 differ from those covered in Figs. 3, 4, 5, and 6 in that the transient peak amplitude is 14 db above the threshold value rather than 18 db. The 14-db transient was simulated at each of two frequencies, 1000 and 10,000 c.p.s. Except for the 4-db difference in amplitude, the input wave forms were similar to those shown in Fig. 3, and the resulting output wave forms of the CBS amplifier are shown in Figs. 7(a) and 7(b).

With reference to the 1000-cycle dynamic performance of Fig. 7(a), the first two cycles at the left of the photograph show the output voltage immediately before the arrival of the transient peak, while the next six cycles correspond to the output voltage immediately after the arrival of the peak. Note that not even the first half-cycle after the arrival of the peak shows any appreciable amplitude overshoot. Thus, the attack time of the CBS amplifier under the above conditions is effectively zero. What may seem more surprising is the fact that there is little wave-form distortion of even the first quarter-cycle after the arrival of the 1000-cycle transient.

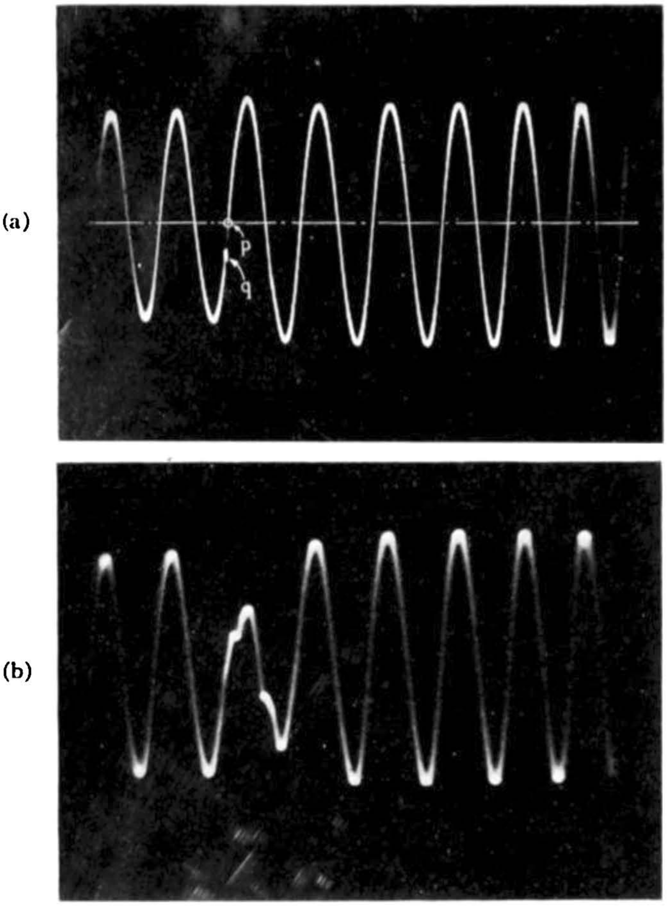

Fig. 7—CBS experimental peak-limiting amplifier, early model. Photographs of output wave forms. Input wave forms are the same as in Fig. 3, except that the amplitude of the transient peak is 14 instead of 18 db.

(a) 1000 c.p.s. No appreciable amplitude overshoot occurs; therefore the attack time is effectively zero. Note that even the first half-cycle is essentially undistorted. The thump component is negligible. The amplifier is seen to "anticipate" the arrival of the peak, since gain-reduction takes place at point *q* in time, whereas the peak does not start until point *p*.

(b) 10,000 c.p.s. No amplitude overshoot is present even on the first half-cycle after the arrival of the signal peak. The first cycle is over-controlled in amplitude.

This excellent performance is attributable to a unique circuit design wherein the automatic-gain-control voltage is a function of the input signal voltage, rather than of the output signal voltage. The control-voltage generating section of the amplifier incorporates large power-type amplifier and rectifier tubes in low-impedance circuit arrangements, resulting in extremely fast development of the automatic control voltage. Another major factor contributing to the exceptional performance shown in Fig. 7(a) is the use of a special time-delay network in the signal channel just ahead of the point where gain reduction takes place. This network acts to delay the signal by approximately 80 microseconds, and the gain is already reduced by the required amount upon the arrival of the peak at the point where gain control is effected. A close examination of Fig. 7(a) will reveal that automatic gain reduction occurs near the point *q* in time, whereas the 14-db peak does not arrive until a later time at point *p*.

The 10,000-cycle performance shown by Fig. 7(b) again illustrates the extremely short effective attack time of the amplifier. Even at 10,000 cycles, the 14-db peak which arrives at the point *p* in time is effectively prevented from exceeding the maximum steady-state value. Fig. 7(b) indicates excessive gain reduction (over-control) for the first cycle after the arrival of the peak. Over-control which persists for so short a time as shown in Fig. 7(b) (approximately 100 microseconds) cannot be perceived by a listening test, and is certainly preferable to under-control, since it renders overmodulation of subsequent equipment impossible.

It can be observed from Fig. 7 that the "thump" component of the amplifier is of very small amplitude, an additional design feature of this unit.

The amplifier described above was developed by E. E. Schroeder of the CBS-Chicago technical staff, under the direction of J. J. Beloungy, and has been used at station WBBM since 1945. Additional amplifiers, based upon this development, are in service in other Columbia Broadcasting System stations and are also available commercially from a well-known manufacturer.

VII. CONCLUSION

It is beyond the scope of this paper to attempt to set forth minimum standards for satisfactory transient performance of peak-limiting amplifiers. However, it seems evident that the more nearly the dynamic performance of a given peak-limiting amplifier conforms to the requirements set forth in this paper, the more satisfactory the operational results are likely to be.

The measuring technique and equipment used to obtain the results described in this paper are applicable to a wide variety of transient measurements of audio devices and systems, such as the transient performance of loudspeakers and recording and reproducing systems, and the build-up and decay characteristics of reverberant acoustical structures.

The technical developments and investigations which form the basis for this paper were carried out under the general direction of Howard A. Chinn, chief audio engineer of the Columbia Broadcasting System.