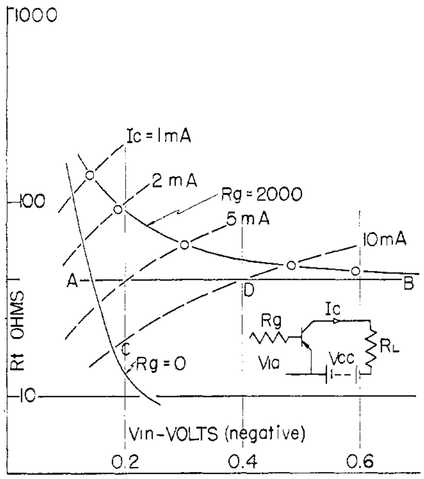

Fig. 1—Transfer resistance.

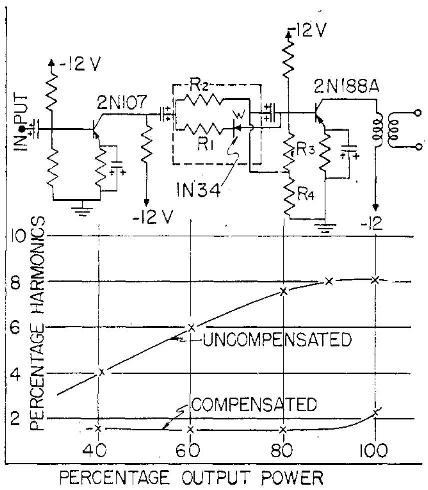

Fig. 2—Compensated amplifier.

propriate value of voltage to be developed across R_g.

The required nonlinear characteristic of R_g is of the same general form as that obtained in a suitably biased semiconductor diode. Such an arrangement is illustrated in the interstage network shown in Fig. 2. In this circuit the interstage coupling is formed by the semiconductor diode W, in series with R_1 and shunted by R_2. Bias is obtained from the voltage divider, R_3 and R_4, forming the bias resistor of a second stage.

The improvement in nonlinear distortion obtained by this circuit is also illustrated in Fig. 2. This shows the relative values of total harmonic content present when using the compensating network and when the network is replaced by a linear resistor equal in value to R_2. Under these conditions the compensated amplifier has a gain of slightly more than 1 db greater than the uncompensated case. By use of interstage networks composed of semiconductor diodes connected in a "back to back" condition, similar results have been obtained with Class A and Class AB push-pull output circuits.

G. W. HOLBROOK
Head, Elec. Engrg. Dept.
Royal Military College of Canada
Kingston, Ont., Can.

Reply to Comments on "Nonlinear Distortion Reduction by Complementary Distortion"*

It is stimulating and valuable when a paper arouses sufficient interest that readers take time to write comments on it. An author almost prefers negative comments than none at all, since this response at least indicates the paper has been read. Therefore, I wish to begin my reply to the correspondents who discussed my paper [1] by thanking them for their helpful comments, which not only serve to illuminate the subject in question further but give me the opportunity to make a few additional informal remarks.

Greiner [2] mentions that practical techniques for complementary distortion reduction have been used by him and others for some years and presents an amplifier-cathode follower combination as an example. It would be most valuable to the readers of these TRANSACTIONS interested in the present subject if he would, in future correspondence, either give references to published work in this field by himself or others or perhaps submit a short paper giving quantitative results of measurements made on his complementary distortion reduction circuits. I believe no one would question his remark that the use of a single-tube voltage amplifier followed by a cathode follower can yield less nonlinear distortion than the voltage amplifier alone. Because of the generally considerably lower distortion of a well-designed cathode follower than a single-tube voltage amplifier, it is surprising that the serial combination of the two can, according to Greiner, yield less distortion than the cathode follower (presumably operating at the same output level) alone. Such a result must require rather special operating conditions, and Greiner has performed a useful service by pointing out its possibility. Even more useful would be specific measured results substantiating the effect in question.

The author was drawn to speculate about complementary distortion reduction by fleeting references (now lost) in the literature on "second harmonic cancellation," and by the surprising results of harmonic and intermodulation distortion measurements made on an active audio filter built in 1955 [3]. This device uses circuits involving cathode followers in combinations somewhat similar to that advocated by Greiner, and it was found that careful adjustment and stabilization of $B+$ and $B-$ voltages and heater current allowed greatly reduced output second harmonic and intermodulation distortion to be obtained as compared to that with unadjusted bias voltages and currents. It is interesting to compare Fig. 8 of this paper [3] (intermodulation distortion vs output voltage) with Fig. 2 of the complementary distortion paper [1] (total harmonic distortion vs a quantity which is proportional to output voltage amplitude if the total distortion is not very high). In spite of the difference between intermodulation and harmonic distortion, there is great similarity between the curves, indicating, as stated in the text [3], that proper operating points can here yield a linearized input-output transfer characteristic. This result shows that whenever one can conveniently adjust and stabilize the operating points of a circuit, adjustment for minimum output distortion should be made to take advantage of whatever built-in complementary distortion reduction is possible. Two recent publications which explicitly use nonlinear complementary distortion networks to produce reduced over-all distortion are cited [4], [5].

Greiner's second point is that it is not impossible to obtain complete harmonic distortion cancellation by complementary distortion as stated in my paper. I agree with Greiner's conclusion; in the paper, my contrary conclusion was not sufficiently restricted to stand correct as written. The paper showed that an infinite number of complementary correction terms were required to cancel completely a given distortion by the techniques proposed in the paper. It should have been made clear that there is no necessity to have a one-to-one correspondence between correcting terms in the completementary series and complementary distortion networks. In ideal cases, a single correction network (see later discussion) may be used to realize the required transfer characteristic.

It is generally believed that negative feedback can only reduce but not eliminate nonlinear distortion. An ingenious feedback arrangement due to Guanella [6] has been shown theoretically and experimentally [7] to allow complete cancellation of nonlinear distortion and interference. Thus, here is another method different in kind from complementary distortion reduction which shows that, unlike taxes, distortion need not always be with us.

Klipsch [8] has stated that while complementary distortion reduction can be accomplished for single frequencies, the restoration or undoing of modulation distortion occurring with multiple input frequencies is impossible. I am grateful to him for bringing up this matter since his statements represent a rather commonly held viewpoint which probably should have been discussed in my paper. Actually, complementary distortion can produce the effect of unmodulating (not demodulating) an intermodulation signal and can thus work as well with multiple as with single frequency input signals. Consider second harmonic distortion followed by postdistortion complementary distortion correction. The output of the original distorting circuit may be written as $e_1 = a_1 e_0 + a_2 e_0^2$. With an input signal consisting of two sinusoids of frequencies f_1 and f_2, the e_0^2 term produces in the output e_1 signal components having frequencies of (f_2+f_1) and (f_2-f_1). It is often thought that once such modulation terms appear, nothing can be done about it. This is not so. After the output e_1 has been passed through a perfect postdistortion circuit of gain b_1, the resulting output will be just $a_1 b_1 e_0$ and will contain no distortion of any kind [1]. Rather than unmodulating the modulated signal, a manifest impossibility and the root of Klipsch's comment, the postdistortion circuit generates a new distorted signal which has modulated components of the proper amplitudes and phases in relation to those at its input

* Received by the PGA, April 29, 1960.

that the combination yields zero, and the final output consists only of the amplified but undistorted input.

These statements may be illustrated for a simple and imperfect postdistortion circuit which only eliminates direct square-law distortion but leaves distortion of distortion components in the output. The input signal e_1 to the postdistortion circuit may be written $e_1 = a_1e_0(1+\epsilon)$, where $\epsilon = a_2e_0/a_1$ and will be considerably less than unity in a practical circuit. With this input, the final postdistortion output may be expressed as [1] $e_2 = a_1b_1e_0(1-2\epsilon^2-\epsilon^3)$. With perfect correction, the ϵ terms would be zero. Since $\epsilon < < 1$, the ϵ^2 and ϵ^3 terms will, however, be very small indeed. Note that the output contains no direct square-law term. Now if e_0 again involves the frequency f_1 and f_2, the second term in e_2 will involve the frequencies $3f_1$, $3f_2$, $(2f_1+f_2)$, $(2f_1-f_2)$, $(2f_2+f_1)$, and $(2f_2-f_1)$. The third term will additionally yield the frequncies $2f_1$, $4f_1$, $2f_2$, $4f_2$, (f_2+f_1), (f_2-f_1), $(3f_1+f_2)$, $(3f_1-f_2)$, $(3f_2+f_1)$, $(3f_2-f_1)$, $(2f_2+2f_1)$, and $(2f_2-2f_1)$. But notice that the coefficients determining the magnitude of these terms will be very small, and, in particular, whereas the original (f_2+f_1) and (f_2-f_1) components arose from a term of relative magnitude ϵ, the final output components involving (f_2+f_1) and (f_2-f_1) arise from a term of relative magnitude ϵ^3 which will be much smaller.

The "insertion-distortion factor" introduced by Cimagalli [9] seems to be a useful measure of the change in total harmonic distortion produced by the insertion of an extra element or circuit in a transmission chain. A similar factor based on intermodulation rather than harominic distortion might also be valuable. Finally, another quantity of usefulness might be the normalized distortion factor, equal to the distortion (harmonic or intermodulation) obtained after insertion of the new element or circuit divided by the original distortion. This quantity would have the virtue of going to zero as the distortion went to zero and of being a direct ratio measure of the distortion improvement or increase.

Waldhauer [10] has made a valuable contribution by pointing out that complementary distortion correction can yield zero output distortion and by showing rather explicitly how the complementary distortion circuit can be realized for complete distortion cancellation in a simple way. When this method is conveniently applicable, it is certainly the one to employ. It involves either having available another circuit exactly like that to be corrected or, alternatively, having available the complete or an approximate specification of the nonlinear transfer characteristic to be corrected. This characteristic must then be realized by whatever means are available and applicable. Then transfer function inversion is required. While it is easy to invert the characteristic of the two-terminal network discussed by Waldhauer, inversion of three or four terminal networks will generally require negative feedback which, in some cases, might be better applied to the original circuit directly.

My colleague, J. P. Pritchard, has also pointed out that Waldhauer's development and his conclusion that perfect distortion correction is possible depend on his assumptions of very low and very high output impedances for the two amplifiers of his Fig. 2. Because these amplifiers will not in practice have zero and infinite output impedances, perfect distortion correction by Waldhauer's techniques will not be possible or will only be approximately realizable in practical cases over a limited amplitude range. These considerations lead again to one of the main conclusions of my article, namely that perfect nonlinear distortion correction over an indefinitely large input amplitude range is impossible. This is not usually a serious restriction, however, since amplitude ranges of interest are always limited. In particular, if the distortion to be corrected arises from a relatively expensive output transformer and pair of power tubes, one would not want to duplicate this equipment and then invert the resulting characteristic in order to achieve distortion cancellation. In this case, the procedures of Holbrook [4] and Sklar [5] are preferable. They amount to a partial realization of the ideal complementary distortion reduction methods discussed by the author and by Waldhauer.

Waldhauer also mentions that the distinction between pre- and postdistortion disappears when his procedure is used. The author also stated that either the first or the second circuit in the transmission chain could be either the distortion producing element of the distortion correcting element. When complete distortion cancellation is achieved, there is naturally no difference in the output whether pre- or postdistortion is used. Only when incomplete correction is used will there by a small difference in the character of the respective partly corrected outputs. As shown in Fig. 3 of the paper in question [1], this difference will usually be negligible in signal ranges of interest.

Finally, I wish to take this opportunity to correct the following printing errors in the paper:

Eq. (5) should read e_0^4 instead of k_0^4;
Second line above (12b) should read $\cos \omega t = 1$;
Eq. (13) should read a_1 instead of a.

J. Ross MacDonald
Central Research Labs.
Texas Instruments Inc.
Dallas, Tex.

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[9] V. Cimagalli, "On the 'insertion-distortion factor'," IRE Trans. on Audio, vol. AU-8, p. 68; March-April, 1960.
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Double Doppler Effect in Stereophonic Recording and Playback of a Rapidly Moving Object*

W. B. Snow[1] describes the ideal stereophonic system as a screen of microphones at the actual stage and a screen of loudspeakers on the virtual stage, each paired microphone-loudspeaker connected with an independent transmission channel.

In such a system, a rapidly moving sound source on the actual stage would be sensed by the observer over a large number of multiple paths on the virtual stage, with a resultant multiple Doppler effect. The same effect takes place with two-track two-channel stereo. As the sound passes an observer on the actual stage, there is a change in pitch of the sound; as it passes a second observer a few milliseconds later, the same pitch change takes place just that much later. Substitute microphones for these two observers, transmit the sound over two loudspeakers, and a single observer hears two sound sources, one of different pitch from the other.

The effect was observed in trying to record a rapidly moving train. The microphones were over 50 feet apart, which exaggerated the effect, making it sound as if there were two trains, or at least two whistles, passing before the observer.

It appears there would be a different virtual source for each channel of a polychannel stereo system. Herein lies at least one difference between stereo reproduction and original sound. Regardless of the accuracy with which stationary or slowly-moving stereo geometry may be reproduced, it appears that an object in motion rapid enough to produce a Doppler effect will contain the distortion effect of there being several sources instead of just one. This problem might be solved by the binaural system—ear spaced microphone and headphones for the listener—but it does not appear possible to resolve the problem with the usual stereo techniques using widely spaced microphones.

A simulated stereo treatment for simple moving objects could probably be highly effective. Snow's "pan-pots"[1]—evidently "panoramic potential dividers"—would transfer a monophonic signal from one side of the stage to the other, with or without a center channel, and the Doppler effect of a single source would be preserved. This could hardly suffice for a series of closely spaced sounds, however.

The stereo microphone may afford a solution. The microphone pair is dependent on directivity for stereo separation and the directivity overlap provides the equivalent of a center microphone in a three-microphone stereo pickup. Experiments to date indicate an excess center signal or monophonic component and therefore less stereo acuity than a two or three spaced microphone pickup. This may present a special problem, but it is believed this single stereo microphone offers important advantages at least in the transducing of sounds from rapidly moving sources.

Paul W. Klipsch
Klipsch and Associates, Inc.
Hope, Ark.

* Received by the PGA, March 4, 1960.
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