An Output-Transformerless Amplifier-Speaker System

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This OTL amplifier requires no critical adjustments. It is used with a high-impedance speaker and a condenser tweeter.

Audio amplifiers without output transformers have been described in several papers within the past few years. As Fletcher and Cooke[1] and Onder[2] have pointed out, there are several good reasons for eliminating the output transformer. The amplitude, frequency, and phase distortions, as well as inherent copper and core losses, all make this transformer either expensive or undesirable.

Many of the output-transformerless amplifiers, however, have been unsuitable for the home music enthusiast because they either had insufficient power output (less than 10 watts), required a great many tubes in parallel, dissipated enough heat to warp the cabinetry, or permitted excessive direct current to flow through the voice coil (forcing it out of the gap or burning it up) if the output-tube cathode-current balance were not accurately maintained. This article describes the design and construction of an amplifier which (a) will feed a wide-range loudspeaker system directly (that is, without an output transformer), (b) has adequate power output (20 watts at 1.5 per cent intermodulation, using 40 and 8000 cps), (c) has a wide frequency range (within 1 db from 9 cps through 30 kc) at both high and low volume levels, (d) incorporates the new extended-range electrostatic tweeters, (e) is in accordance with the results of a great deal of fundamentally sound psychoacoustic research which has recently been published, and (f) is easy to assemble and wire. It is intended to be used as the main power amplifier, fed by a preamplifier or tuner with an output of 1 volt or so. A view of the complete amplifier appears in *Fig.* 1, while the two-element speaker system is shown in *Fig.* 2.

The schematic wiring diagram is *Fig.* 3. The power transformer has been retained for three important reasons: (a) a high plate-voltage supply at low current is required to enable the 5687 stage to furnish adequate signal voltage to the following grids; (b) an electrostatic shield is desirable to reduce noise and hum from the power line; and (c) the regulating action of a filament transformer greatly reduces the initial rush of current into the heaters when the amplifier is turned on, and this action prolongs tube life. (In military and naval electronic equipment, the operation of heaters or filaments in series is forbidden because it results in short and erratic tube life.)

The amplifier input is across a 1-megohm volume control, which may be used as a pre-set. The input stage is followed by a conventional phase splitter. This phase splitter is self-balancing, has low distortion, and has an input impedance of about 10 megohms. These first two stages use a ruggedized tube, the GL-5814A, which is similar to the 12AU7 but has a very low heater-to-cathode leakage, which is important in a phase splitter of this type. A direct current supply is used on the heater of this tube to eliminate hum.

The 5687 is also a rugged, military-type tube which is capable of being operated at relatively high plate voltages without electrolysis of the glass at the base.

The 6337, which was developed in the spring of 1954 by Chatham Electronics Division of the Gera Corp., is the tube that has made this amplifier possible. With a transconductance of 45,000 umhos, plate dissipation of 80 watts, plate resistance of only 60 ohms, and a hard glass envelope, it is an audio output tube with exceptional power-handling capabilities, rugged internal construction, and a very long life. In conventional transformer-coupled circuits[3] it is capable of delivering 7 watts at 3 per cent IM (for one pair of tubes in class-A operation). In this circuit it is operated at only 60 per cent of its maximum plate dissipation, and one-third of the output

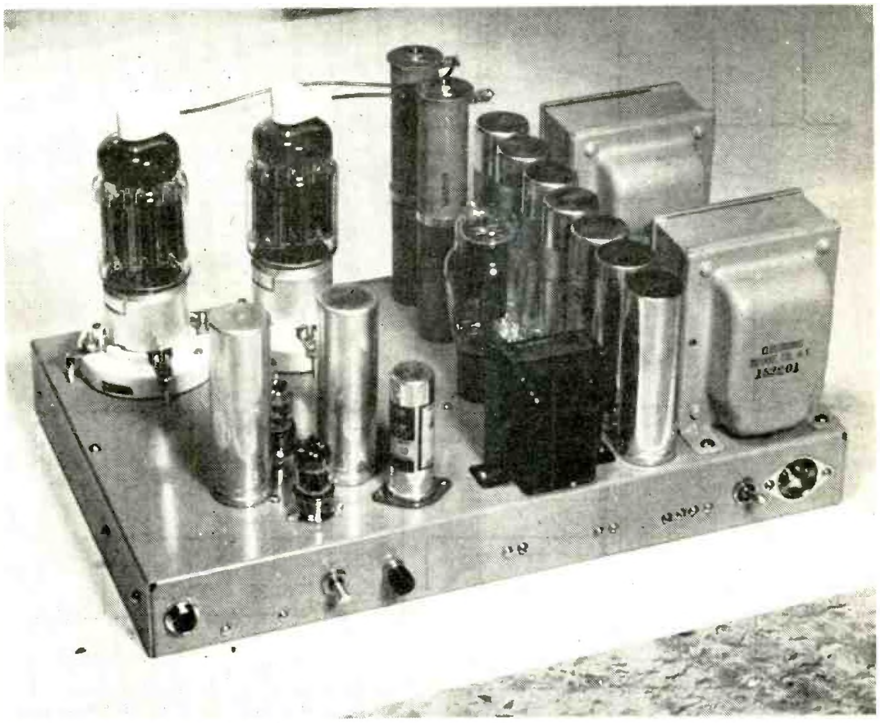

Fig. 1. The complete amplifier, with power supply, is on an aluminum chassis measuring 11 x 17 x 2 inches.

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[1] E. W. Fletcher and S. F. Cooke, "Cathode-follower loudspeaker coupling," *Electronics*, Nov. 1951, pp. 118–121.

[2] Kerkn Onder, "Audio amplifier matches voice-coil impedance," *Electronics*, Feb. 1954, pp. 176–179.

[3] Curtiss R. Schafer, "30-watt high-fidelity audio amplifier," Audio Engineering, July 1948, pp. 21–23.

power is dissipated in the plate-feed resistors, so the useable power output is about 20 watts. The plate-feed resistors R_{18} and R_{19} stabilize the load impedance at 167 ohms, despite the increase in impedance at the higher frequencies which characterizes moving-coil loudspeakers.[4]

The power transformer T_1 is available as type 1570461 from Electronic Transformer Co. It may also be duplicated by combining other power transformers which the constructor may have on hand. The current ratings of the various windings are as follows: 6.3 volt (Y), 1 amp.; 6.3 volt (Z), 14.5 amp., c.t.; 10 volt, 0.4 amp.; 5 volt, 2 amp.; 1000 volt, c.t., 40 ma.

The output of the 10-volt winding is rectified in a full-wave bridge rectifier and filtered for the heater of the 5814A. The value of the 15-ohm series resistance R_{25} should be set so that the voltage at the heater terminals of the GL-5814A is 6.0 volts at a power-line voltage of 117.

The low-voltage, high-current plate supply for the output stage uses four 1N158 fused-junction germanium rectifiers in a paralleled half-wave voltage-doubler circuit, providing 250 volts at 800 ma. The 1N158 is a very efficient rectifier, having a drop of only 1.4 volts at full load. The 250 µf capacitors are each made up of two 125 µf units in parallel. A filter choke is used to ensure adequate filtering. (This power supply, incidentally, is almost exactly what is required for the operation of an output stage using two power transistors, such as the Minneapolis-Honeywell type 2N57, as these transistors draw collector currents up to 700 ma each; the only difference is that a regular half-wave rectifier circuit may be used instead of a voltage doubler.) It is a common fallacy to assume that push-pull stages require less filtering in the plate supply. It is true that hum is cancelled out in a well balanced push-pull stage under zero-signal, quiescent conditions; however, the stage is unbalanced the instant a signal comes through, and the hum frequencies react with a signal frequencies to increase the over-all intermodulation distortion, especially at low volume levels.

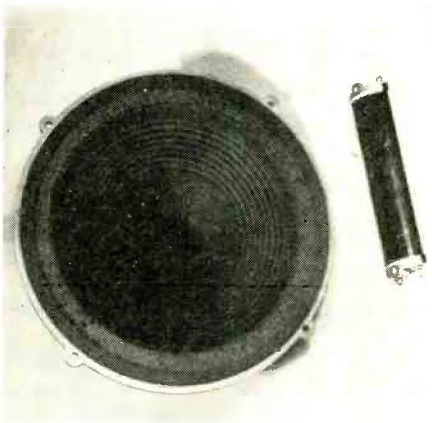

Fig. 2. The speaker, obtained from the maker on special order, and the Philco tweeter.

It should be noticed that one side of the 117-volt power line is grounded in the amplifier. For this reason, a polarized receptacle should be installed where the amplifier will be used, and the cord conducting power to the unit should be fitted with a polarized plug. One side of the 117-volt line is grounded at the distribution transformer, and also where the line goes through the entrance switch; this side of the line will show no voltage, or only a few volts, when an a.c. voltmeter is connected between it and a good ground. This side of the line

[4] Edgar M. Villchur, "Handbook of sound reproduction: Loudspeakers," AUDIO ENGINEERING, March 1953, pp. 32–34.

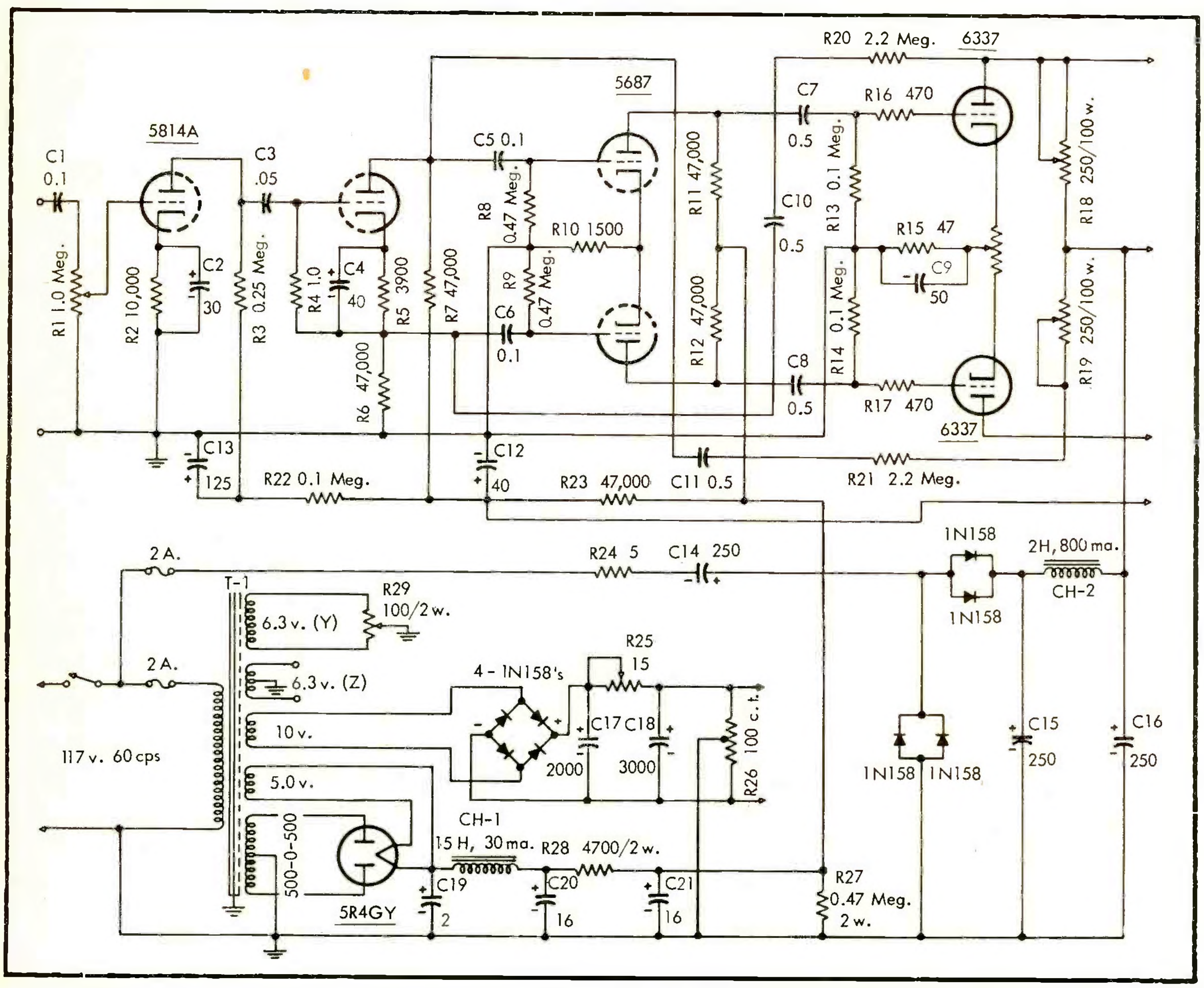

Fig. 3. Complete schematic diagram of the amplifier and power supply. Key to the new amplifier is the 6337 tube with its low plate resistance.

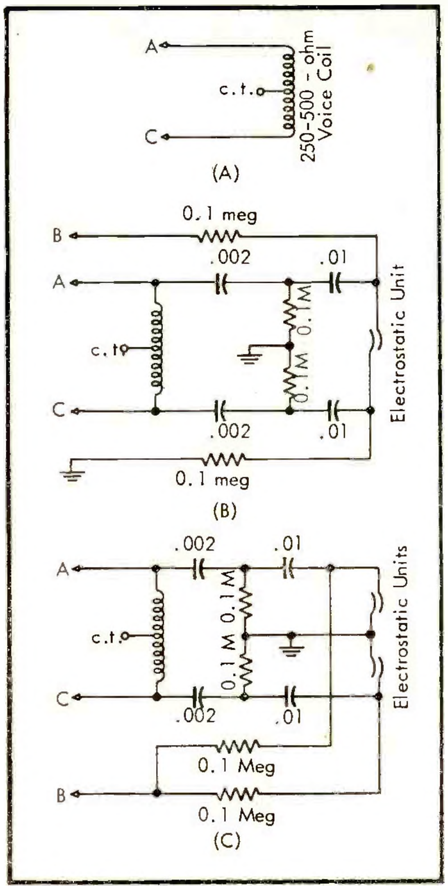

Fig. 4. Three methods of connecting speakers to the amplifier. At (A) a single high-impedance speaker; at (B) a woofer and electrostatic speaker; at (C) a woofer and two tweeters.

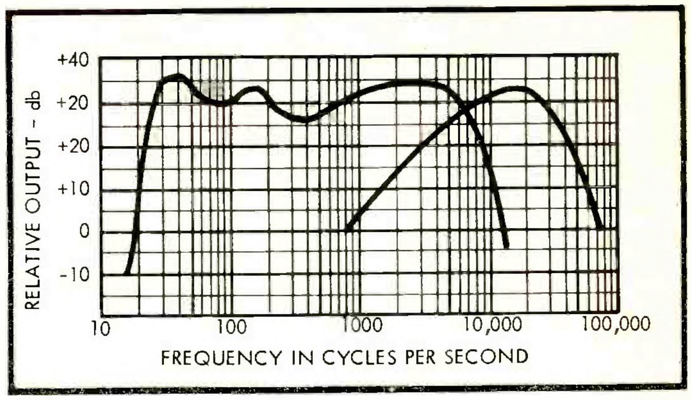

Fig. 5. Over-all system response from each of the speakers when one woofer and one tweeter are used.

should be the same as the side that is internally grounded in the amplifier, and in addition, a heavy lead should be run from the binding post on the chassis to a good water pipe or radiator ground.

The power transformer and both chokes are mounted with their laminations perpendicular to the chassis; this results in the least amount of magnetic flux being radiated into the chassis. All ground returns must be made to a single point; the arrangement preferred here is a group of six solder lugs fanned out under the nut and split lockwasher of one of the screws holding the 15-henry choke. The use of an aluminum chassis also results in less hum from magnetic flux conduction. The chassis should be finished by being etched, anodized, and then having a coat of enamel baked on at about 35 deg. F. for 3 hours.

Negative Feedback

A great deal of negative feedback is not worthwhile in an audio amplifier. In the first place, practically no increase in speaker damping is achieved when the output impedance of the amplifier is made less than about one-third the impedance of the speaker.[5] This is because the electrical and mechanical impedances of the speaker become the controlling factors.

In the second place, many professionally designed amplifiers are regenerative at the low and high ends of their frequency ranges. Low-frequency regeneration is obnoxious because it causes the amplifier to overload with the rumble from a turntable. High frequency regeneration is undesirable because it gives a tinny or "hashy" quality to the highs; this tinny quality is often blamed on the metallic diaphragms used in most tweeters. High-frequency regeneration, as well as low, is caused by phase shifts in the coupling networks in an amplifier. so that the feedback is actually regenerative rather than degenerative, and it has been very much in evidence in a great many recent amplifier designs, as shown by the little ripples which ride the top of a square wave passed through these amplifiers.

In the present amplifier, about 2 per cent of the voltage on each output plate is fed back degeneratively to the input of the preceding stage. This is sufficient to stabilize gain and give some reduction in output impedance, and because the feedback is over only two stages, there is no evidence of either high or low-frequency regeneration.

All resistors are 1-watt unless other wattages are specified. The 270 ohm resistors R_{18} and R_{19} are required in this circuit because a high-resistance voice coil cannot carry the plate currents for the output tubes. Isolating capacitors are not necessary however, because no direct current can flow through the voice coil even if the plate currents are badly unbalanced. Direct current will flow through the voice coil, however, if the coil is shorted to either the inner or outer pole-piece. For this reason, do not attempt to use a speaker with a rubbing voice coil. If the coil is properly centered, the usual insulation is adequate for the low plate voltage used.

R_{18} and R_{19} should be adjusted by means of the sliding taps so that their resistances are approximately equal, that is, within 2 or 3 per cent of each other. This is easily done with an ordinary ohmmeter, not by reading the absolute values of resistance, but by seeing that the deflection of the meter is the same for both resistors.

No critical adjustments of any kind are required on this amplifier. Plate-current balance in the output stage need be only an approximation, for good low-frequency response does not depend upon balancing out the direct current component in the primary of an output transformer. Balance within 10 per cent may easily be achieved by connecting a d.c. voltmeter between amplifier output terminal *B* and the voice coil centertap, and then adjusting R_{30} for a minimum reading on the voltmeter, reducing the voltage range of the meter as the unbalance voltage drops. If a speaker is used that does not have a tapped voice coil, adequate balance may be realized by adjusting R_{30} so that the voltage drop across R_{18} is equal to the voltage drop across R_{19}. Once the adjustment of R_{30} is made it may be forgotten for a year or two, as plate-current drift in the 6337 is negligible.

Loudspeakers

Any one of three speaker arrangements may be used. These are shown in *Fig*. 4. The one in (A) employs a 12-inch model with a centertapped 250-ohm copper voice coil, made up through the courtesy of the manufacturer. At this time, it is not considered it feasible to "make a speaker with an aluminum voice coil having an impedance of 250 ohms. The trouble is that aluminum wire is very fragile, and it is extremely difficult to tin, even by ultrasonic means, as the wire simply disappears during the process of tinning if it is too fine. It is also not possible to obtain aluminum wire in a very fine gauge because it is too fragile to handle." The speaker is simply connected across the amplifier output, plate-to-plate; a wire should be run from the frame of the speaker to the ground binding post on the amplifier chassis.

The frequency response curve of this speaker shows that with the copper voice coil it is deficient at the high frequencies (*Fig*. 5). One way of compensating for this deficiency is to use about 30 db treble boost in the preamplifier taking care to see that the treble boost complements the treble droop in the speaker so that a fairly flat response is obtained from the combination. The unit should be used in an enclosure that will provide adequate loading at the rear of the cone by means of a folded exponential horn.[6]

The best combination, however, uses

(*Continued on page 42*)

[5] Figs. 12-14 (damping effect of amplifier source impedance on speaker), AUDIO ENGINEERING, August 1953, p. 27.

[6] H. F. Olson and R. A. Hackley, "Combination Horn and Direct Radiator Loud-Speaker," *Proc. I.R.E.* Dec. 1936, pp. 1557-1566.

one or two electrostatic tweeters, as shown in *Fig*. 4 (B) and (C). Three of these tweeters are presently available: the Philco shown in *Fig*. 2; the "Kilosphere," made by Columbia Records; and the Kingdom-Lorenz SKL 100. The SKL 100 and the Korting are described in the literature.[7, 8] The author used a Western Electric 640A condenser microphone as a tweeter during the initial development of this amplifier-speaker system. This use of the 640A has also been described in the literature.[9] The high frequencies from the 640A, while very clean, were too sharply beamed; the Philco unit, constructed as a section of a cylinder, diffuses the highs very nicely, especially when used in pairs with one unit on each side of the woofer.

Electrostatic speakers, as such, are not new. The Kyle electrostatic speaker was used with Peerless radio receivers about 25 years ago, and gave cleaner reproduction than the dynamic speakers of that day. The Kyle speaker required a polarizing voltage of about 1,000 volts, however, and insulation ruptures were common.

Basically, the electrostatic speaker consists of a rigid back plate, a very thin dielectric, and a foil membrane which forms the active or vibrating sound radiator. If an alternating voltage is applied across the back plate and the membrane, the electrostatic forces cause the membrane to be attracted to the back

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[7] Marvin Hobbs, "Electrostatic speaker accents high frequencies," *Electronics*, Nov. 1954, pp. 143–145.

[8] Data Sheet on Kingdom/Lorenz Electrostatic Loudspeaker, Model SKL 100.

[9] I. Rudnick and M. N. Stein, "Reciprocity free-field calibration of microphones to 100 kc in air," *Jour. A.S.A.*, Nov. 1948, p. 824.

plate twice in every cycle; this attraction results in a vibration of the membrane which produces a sound having twice the frequency of the applied alternating (signal) voltage.

If a d.c. polarizing voltage is applied between the back plate and the foil, the signal voltage merely is added to or subtracted from the steady polarizing voltage, and hence the frequency of the radiated sound is the same as the frequency of the signal.

In order to prevent tearing of the foil, its movement must be restricted, and this means that the electrostatic speaker should be fed only signals above 4 to 5 kc. The R-C coupling networks shown in *Fig.* 4 provide a high-pass filter, so that the tweeter is worked at normal listening levels only above 7500 cps. The exact component values shown in *Fig.* 4 are for the Philco units used with a special woofer; the experimenter will certainly want to vary these values for different makes of speakers, different types of enclosures, and different room acoustics. The capacitance of the Philco unit is .0024 μf. The approximate composite and overall response curves are shown in *Fig.* 5.

A polarizing potential of around 250 volts is suitable for both the Philco and the Korting, and the connections shown in *Fig.* 4 will provide this value. The voltage may be increased to 450 volts or so for the Philco and Korting (but not the Kingdom-Lorenz), and in this case terminal B in *Fig.* 4 should be connected to terminal D rather than B in *Fig.* 3.

The circuit symbol for an electrostatic tweeter is as shown in *Fig.* 4; the outline of a crescent indicates the rigid back plate, and the arc to the right of it indicates the foil radiating surface.

The author believes that for the best results in the natural reproduction of sound, the amplifier and speaker system must be considered as an integrated unit. The performance of the output stage is intimately related to its load,[10] the phase shifts in the speaker or speakers are very important in determining the behavior of an over-all inverse feedback loop.[11] Much work is still to be done before we really known how to measure the transient response of an audio system.[12]

The author hopes that this article will add to the interest in direct-coupled amplifier-speaker systems, and that those who build this amplifier will be stimulated to make improvements in it and report their improvements in the literature.

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[10] A. W. Stanley, "The output stage; effect of matching on frequency response," *Wireless World*, Aug. 1946, pp. 256–259.

[11] Charles A. Ewaskio and Osman K. Mawardi, "Electroacoustic phase shift in loudspeakers," *Jour. A.S.A.*, July 1950, p. 444.

[12] Carl Olof Olsson and Kazimierz Orlik-Ruckemann, "The Dampometer," *Electronic Engineering*, Oct. 1954, pp. 420–428.