

A High-Quality SOUND SYSTEM for the Home

H. F. Olson and A. R. Morgan
RCA Laboratories

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Analysis of the problems encountered by the audio enthusiast in designing and building his own relatively low-cost, high-quality audio system.

The main objective of this article is a rationalization of the problems confronting the enthusiast for good sound reproduction.

The statement, "high quality sound reproduction," implies a desire for realism or naturalness in the reproduced sound. The ideal in sound reproduction would result from subjecting each of the listener's ears to the exact sound that would be received by attending the original source. To achieve this ideal, resort must be made to such complications as Binaural¹ or Auditory Perspective^{2,3,4} Reproducing Systems. These systems are not within the province of practicality and need be discussed no further.

Practical considerations dictate the use of monaural or single channel reproducing systems. The ideal of this system would be an exact reproduction, from the loudspeaker, of the sound impressed on the microphone of the system. To the enthusiast, then, the basic problem involves the cost of a satisfactory approach to this ideal. He finds that he must weigh such factors as response, distortion, and power output against cost.

A reasonable solution for the problem will result from limiting the demands on the system to those which are truly needed for satisfactory high-quality sound reproduction in the home. If this approach

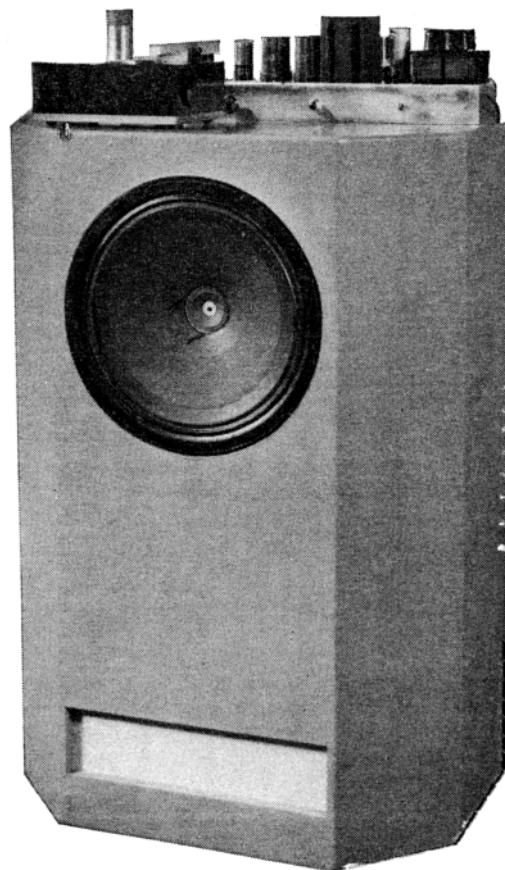


Figure 1: Complete sound system including a 9JY record changer, amplifier, and the RCA type LC1A loudspeaker and cabinet assembly.

¹Olson and Massa; "J. Soc. Mot. Pic. Eng.," Vol. 23, No. 2, p. 63, 1934.

²Fletcher, H.; "J. Soc. Mot. Pic. Eng.," Vol. 22, No. 5, p. 314, 1934.

³Maxfield, Colledge, Friebe; "J. Mot. Pic. Eng.," Vol. 30, No. 6, p. 666, 1938.

⁴Fletcher, H.; "J. Acous. Soc. Amer.," Vol. 13, No. 2, p. 89, 1941.

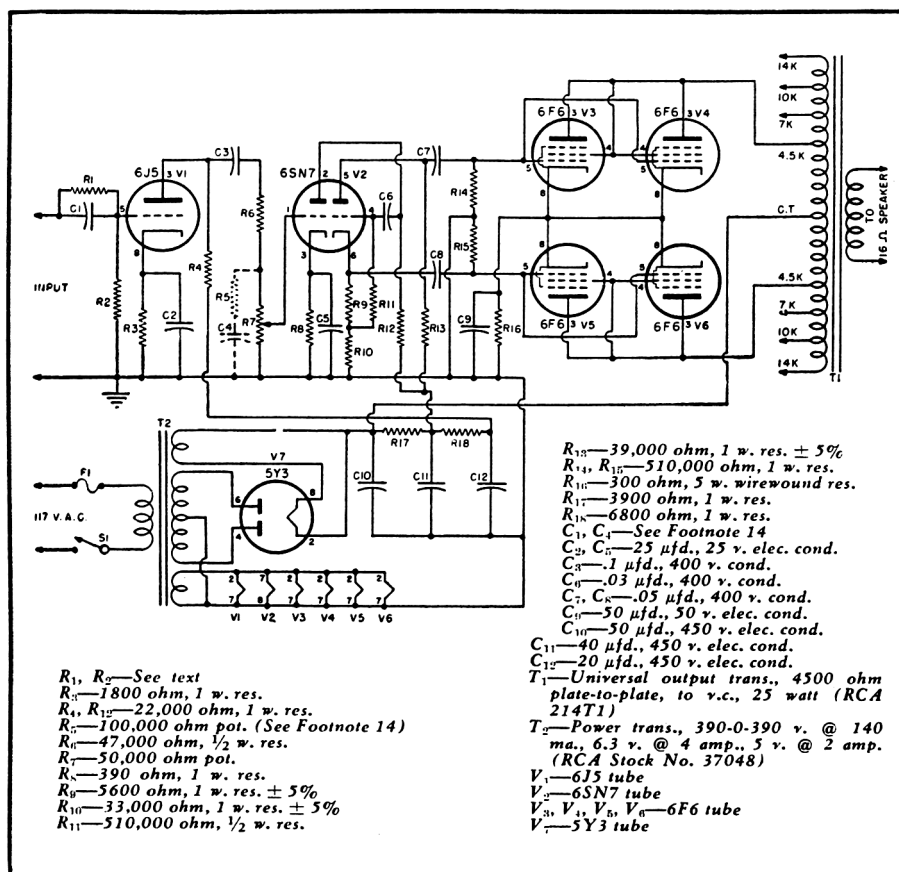


Figure 2: Diagram of triode amplifier. It is straightforward and easy to duplicate.

is used, it is possible to develop a wide range, low distortion sound reproducing system in which the cost is comparable to the cost of mass produced systems. It is a further objective of this article to describe in detail the elements and performance characteristics of a practical high-quality sound reproducing system consisting of a record player, amplifier, loudspeaker unit, and cabinet. This description will enable the enthusiast to assemble a high-quality sound reproducing system at a moderate cost.

Frequency Response

To determine the frequency response needed for an ideal sound reproducing system, it is necessary to consider, in combination, the response of the human ear and the frequency ranges encountered in speech and music. The frequency range of the average normal ear⁵ is from 20 to 20,000 cycles. It is likely that frequencies higher and lower than the limits of the ear will, at times, be encountered in music or in certain noises. It has been shown^{6,7} however, that the frequency range required for no appreciable loss in quality of reproduction is from 40 to 15,000 cycles. This range, therefore, might well be treated as an ideal.

Any attempt to evaluate the effect of restricting the frequency range of reproduction involves a personal judgment of quality and for all but minor range restrictions can be very confusing. Since the purpose of this discussion is to establish a criterion for high-quality reproduction, the drastic frequency range restrictions are, fortunately, not important. If terms such as: "Almost as satisfactory," or "slight effect upon tone quality," be taken as a criterion, it can be shown⁶ that a frequency range from 60 to 10,000 cycles would be indicated.

The choice between ideal and restricted frequency ranges reduces to a balance between cost and performance. It appears, therefore, that the enthusiast must make his own decision as to the desirability of using less than ideal response.

Distortion

The allowable amount of distortion in a high-quality sound system is rather difficult to specify. The difficulty lies in the lack of any but general correlation between subjective and objective tests on distortions in sound reproducing systems.

Some idea of the subjective effects of distortion can be obtained from a study of the masking curves of the human ear. It will be seen, for instance: that the higher order harmonics are more easily discerned than the lower order harmonies; that the masking of harmonics increases as the signal level increases; that difference tones may be of more importance than the harmonics. With the complex waves of speech and music it becomes more difficult to speak, even in generalities. The amount of masking depends on the spectral distribution of the sound. A general idea can be obtained from a consideration of the masking effects of wide-band thermal noise. It is seen that at higher levels it becomes increasingly difficult to detect harmonics. The authors and their associates have reached a similar conclusion regarding the masking of distortion by higher level speech and music. Furthermore, it has been observed that the sensitivity of the ear to distortion in music appears to be a maximum for sound levels in the vicinity of 70 to 80 db.

If an attempt is made to evaluate the subjective effects of distortion, it immediately becomes evident that a continuous scale of values is impossible. Resort must be made to grouped gradations, such as; perceptible, tolerable, or objectionable. A perceptible level of distortion is dependent on experience and is, therefore, a fairly definite quantity. Tolerable and objectionable levels of distortion are dependent on personal opinion and are, therefore, very indefinite.

Obviously, the perceptible level of distortion can be used as an ideal—one can hardly ask for more than being unable to hear the distortion. For the type of distortion contemplated, for the frequency response contemplated, and for a sound level of 75 db., it has been shown⁸ that a total r.m.s. distortion of approximately 0.75% is perceptible to critical listeners. This figure, therefore, is selected as the ideal for distortion performance. As pointed

⁵ "Bell laboratories Record," Vol. 12, No. 10, p. 314, 1934.

⁶ Snow, W. B.; "J. Acous. Soc. Amer.," Vol. 3, No. 1, Part 1, p. 155, 1931.

⁷ See "Tanglewood Demonstrations," later in this article.

⁸ Olson, H. F.; "Elements of Acoustical Engineering," 2nd Edition, pages 488–491.

out before, the ear is not as critical at higher sound levels. It is probable, therefore, that this ideal figure can be relaxed for higher sound levels.

Any compromise with the ideal of distortion performance becomes so involved, with the items mentioned previously, that a single answer as to what constitutes tolerable distortion is unavailable. Distortions greater than ideal are most likely to occur at the higher power or sound levels. If it is assumed, for the moment, that ideal distortion performance can be achieved at intermediate (and lower) levels, then the concern is reduced to consideration of tolerable distortion at higher levels. It is the opinion of the authors that, for the type of reproduction contemplated in this article and for sound levels of 90 db., total r.m.s. distortions of 2 to 3% are tolerable.

Power Output

The electrical power input and sound power output of a loudspeaker are related by the efficiency of the loudspeaker. The electrical power requirements are, therefore, directly dependent on the sound level requirements.

Sound level requirements will vary, depending on individual tastes. It appears that, in the home, a habit pattern has developed from radio listening. It would seem that the radio volume control is adjusted so that speech is reproduced at ordinary conversational level and then no change is made as the program changes to music or whatever. Ordinary conversation has an average sound level of approximately 70 db. Opinion and scattered tests of sound levels found in home reproduction offer a figure ranging from 65 to 75 db.

Numerous demonstrations of high fidelity sound reproduction have been made to visitors to the *RCA Laboratories*. The demonstrations were made in the Living Room Laboratory which is representative⁹ of a typical living room in a house or apartment. The average power input to the loudspeaker for these demonstrations was approximately 0.050 watt and resulted in an average sound level of approximately 80 db. This sound level has been objected to by some as being too loud, but never as being too low.

⁹H. F. Olson; "J. Acous. Soc. Amer.," Vol. 15, No. 2, 96-102, Oct. 1943.

From the above, it would seem that an average sound level of approximately 75 db. would be adequate for most home reproduction. The power corresponding to this sound level would be approximately 0.016 watt.

For satisfactory performance, a sound reproducing system must be able to handle the power peaks encountered in speech and music. It has been established,^{10,11} that the ratio between r.m.s. peak power and r.m.s. average power in speech and music is approximately 10 db. For an average power level of 0.016 watt the peak power would, therefore, be approximately 0.160 watt. Using round numbers and a moderate safety factor we have the surprising result that a $\frac{1}{4}$ to $\frac{1}{2}$ watt amplifier would give satisfactory performance in many home installations.

There are, of course, many persons who desire the illusion of placing a large orchestra in their living rooms. Let us assume that the sound levels experienced in a concert hall for "full orchestra" from a large symphony orchestra will be adequate. It can be shown¹² that the peak sound level at a desirable seat in such a concert hall is not likely to exceed a value of 100 db. Extrapolating from the above figure of 0.050 watt corresponding to a sound level of 80 db. in an average living room, we deduce that peak sound levels of 100 db. would correspond to peak powers of 5.0 watts. It appears, therefore, that we are justified in limiting the power requirements of the amplifier and loudspeaker to approximately 5.0 watts.

Amplifier

The choice of an amplifier for a high fidelity sound reproducing system has become one of the most discussed problems in the audio field. A discussion of the problem immediately becomes involved with arguments, pro and con, concerning triodes, pentodes, feedback, power output, distortions, etc. To the innocent bystander, the consensus of these discussions, is an amplifier having, the more power the better, the lowest possible distortion at maximum power and, as a result, a disappointingly high cost.

¹⁰Wolf, S. K. and Sette, W. J., "J. Acous. Soc. Amer.," Vol. 2, No. 3, p. 384, 1931.

¹¹Sivian, Dunn and White; "J. Acous. Soc. Amer.," Vol. 2, No. 3, p. 330, 1931.

¹²"Bell Laboratories Record," Vol. 12, No. 10, p. 314, 1934.

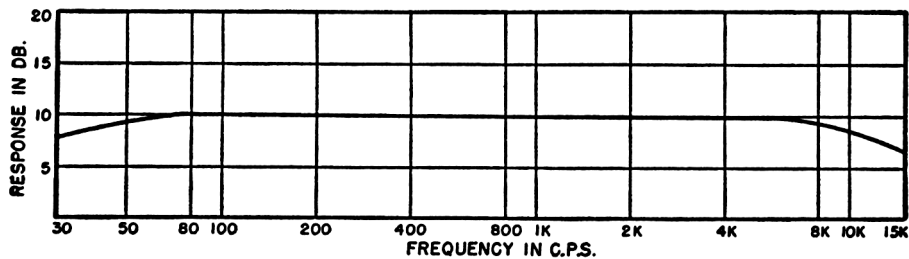


Figure 3: Output response of amplifier for constant voltage at grid of the input tube.

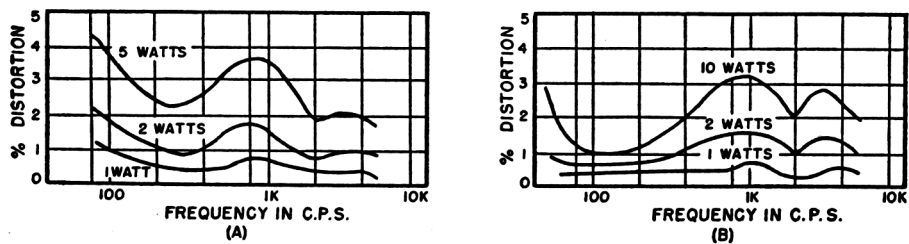


Figure 4: (A) Total harmonic distortion of the RCA 515S1 and (B) the RCA LC1A speakers.

The price of an amplifier depends on the performance required from the amplifier. Again, it seems proper, therefore, to insist only on that performance which is truly necessary. The necessary requirements for the amplifier are essentially the same as the system requirements set down before. It is very important to consider the distortion generated by the amplifier for the power level at which it will be most used. That power level would probably be of the order of $\frac{1}{4}$ watt and the distortion would be all the more important because of the increased acuity of the ear at the corresponding loudness level.

The selection of the amplifier configuration to meet the desired performance brings up the argument concerning triodes, pentodes, feedback, etc. It is generally conceded that the triode is superior to the pentode on a distortion basis. Consequently, the choice lies between the triode and the pentode with feedback. Triode amplifiers have been in commercial use for many years and, it would appear, have almost become a standard for comparison. It is claimed by many that pentode amplifiers with feedback can be made as good as or better than triode amplifiers. There is no reason to doubt this

claim; however, it should be pointed out¹³ that the price for the improvement to be obtained by feedback is the necessity of design control over a considerable frequency range below and above the useful frequency range of the amplifier. It is tacitly assumed here that the benefits of feedback will be required over the whole of the useful frequency range. The particular reasons for wanting to use a pentode derive from the improved power sensitivity and plate efficiency of such tubes. In an over-all sense these advantages are reduced, when feedback is applied. Negative feedback always reduces the over-all gain of the amplifier, and hence the advantage of power sensitivity of the pentode is reduced. The saving in power supply cost, in a pentode-feedback amplifier would be practically used up in supplying the necessary quality of components to allow the desired amount of inverse feedback.

Summing up, it appears that from a performance standpoint there is probably little difference between a triode amplifier and a *properly designed* pentode-feedback amplifier. From a custom design and construction standpoint the inherent simplicity of the triode amplifier is certainly to be pre-

¹³Bode, H. W.; "B. S. T. J.," Vol. 19, No. 3, p. 421, July 1940.

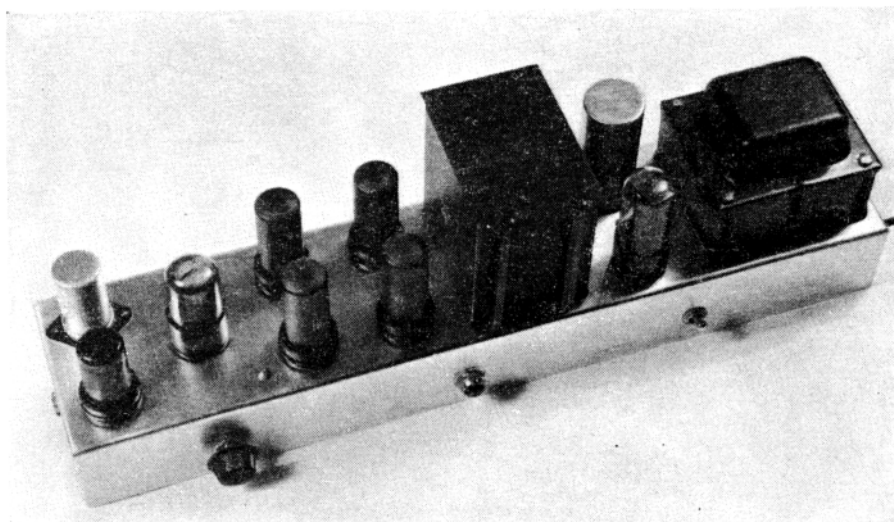


Figure 5: Over-all top chassis view of the triode amplifier described in the text.

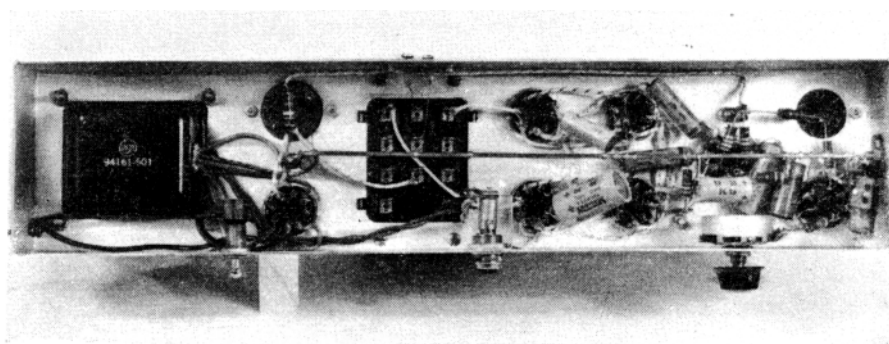


Figure 8: Under chassis view of the triode amplifier showing simplicity of wiring.

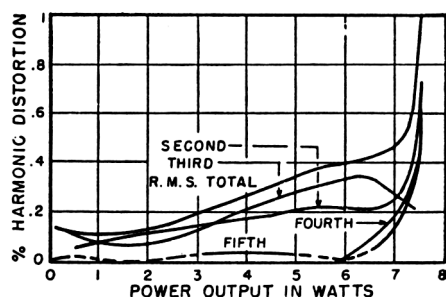


Figure 6: The 2nd, 3rd, 4th, and 5th harmonic distortion components and total r.m.s. harmonic distortion as a function of power output measured at 400 cycles.

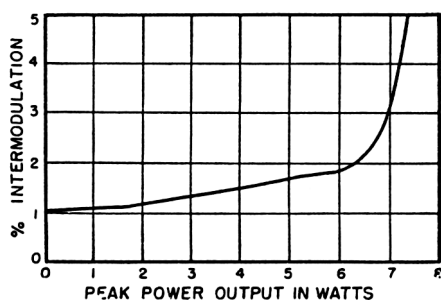


Figure 7: Intermodulation distortion produced by combined inputs of 100 cycles and 2000 cycles. The amplitude of the higher frequency is one-fourth of the lower frequency. The curve shows total distortion, that is, the results have not been divided by 4.

ferred over the inherent complicity of the pentode-feedback amplifier. There can hardly be any other conclusion than to recommend a triode amplifier for a custom type system, provided the desired performance is obtainable with the relatively few output triodes available.

A triode amplifier using readily available tubes and as simple a construction as possible has been developed. Photographs of the amplifier are shown in Figs. 5 and 8. The circuit diagram is shown in Fig. 2. The component specifications are given in the parts list.¹⁴ The simplicity of the amplifier is obvious and also leaves little to be desired.

As can be seen in the following exposition of data, the amplifier performance is well within the specifications developed above. Fig. 6 shows the harmonic distortion of the amplifier for resistive loading for 400 cycle input. The distortion is shown on an individual harmonic and on a r.m.s. total basis. To be noted is the lack of higher order harmonics. For those who may be interested in the intermodulation distortion of the amplifier the results are shown in Fig. 7. The results of difference tone generation tests on the amplifier are shown in Fig. 9. The test consisted of introducing, to the amplifier, two equal primary voltages having a small difference in frequency. Then, the relative amplitudes of corresponding primary output voltages and the difference tone generated were determined by means of a wave analyzer. The result has been expressed as the ratio of the amplitudes of difference tone to either output voltage, in percent. The tests were conducted for primary voltage frequencies in the vicinity of 1000, 5000, and 10,000 cycles, and for difference frequencies ranging from 50 to 500 cycles. The power levels at which the tests were made are on the basis of the peak power obtained with the two primary voltages acting simultaneously. From a consideration of Figs. 6, 7, and 9, it is readily seen that the amplifier leaves

¹⁴Resistors R_1 and R_2 and C_1 are included for frequency compensation purposes and are discussed in the section on "Over-all system." If a high frequency tone control is desired, the dotted components may be added in shunt with the volume control. The 100,000 ohm tone control, R_5 should have a means for providing an open circuit at the maximum resistance end of rotation. The condenser, C_4 may have a value ranging from 1000 to 2000 micromicrofarads. The former value will provide a maximum attenuation, at 10,000 cycles, of 6 db. The latter value will provide 10 db. at the same frequency.

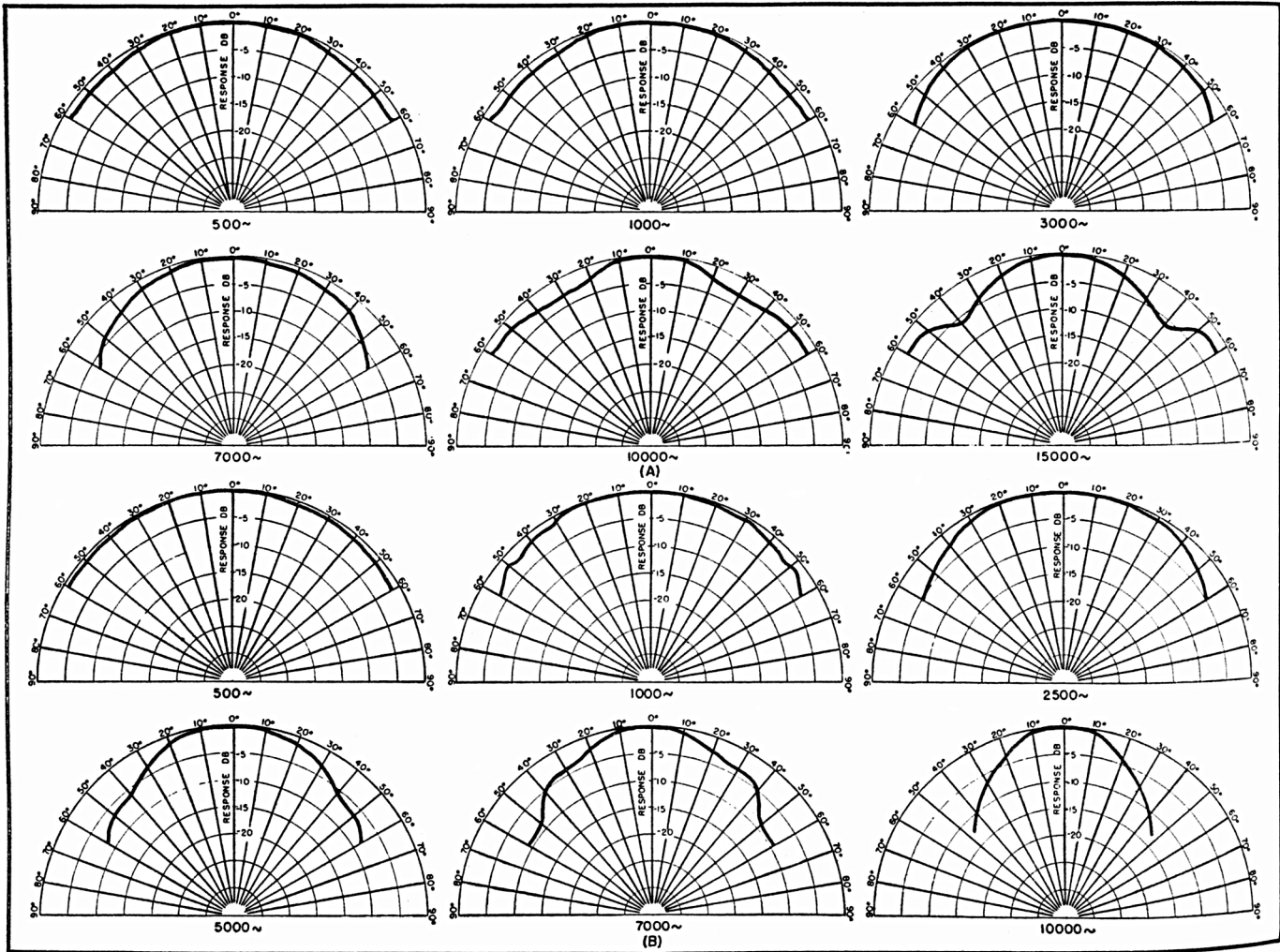


Figure 11: (A-Top two rows) Directional characteristics of the RCA LC1A speaker, and (B-bottom two rows) of the RCA 515S1 speaker.

little to be desired for output powers up to 5 watts. The frequency response of the amplifier is shown in Fig. 3. A comparison with the loudspeaker response shown in Fig. 15 proves the amplifier response to be adequate.

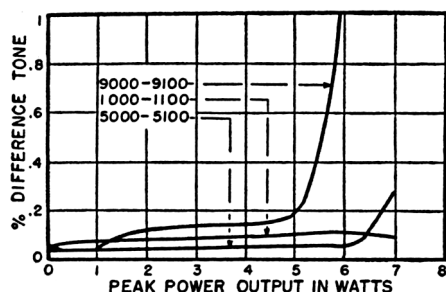


Figure 9: Difference tone generation produced by an input of two h.f. components.

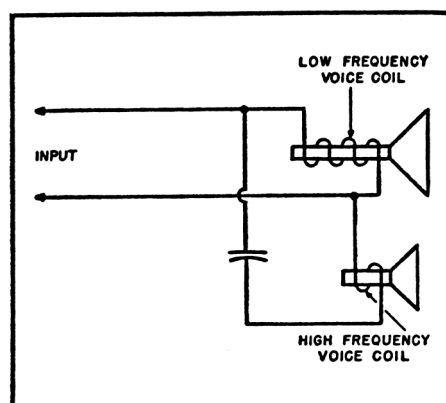


Figure 10: Electrical crossover network of the duo-cone loudspeaker mechanism.

Loudspeaker Mechanism

Two duo-cone loudspeaker mechanisms were used for this reproducing system, namely the *RCA LC1A*¹⁵ and the *RCA 515S1*.¹⁶ The LC1A duo-cone is the custom-built deluxe loudspeaker

¹⁵Olson and Preston; "RCA Review," Vol. 7, No. 2, page 155, 1946.

¹⁶Olson, Preston, Cunningham; "RCA Review," Vol. 10, No. 4, page 490, 1949

mechanism covering the frequency range from 40 to 15,000 cycles with a broad directivity pattern and low distortion, while the 515S1 is the mass-produced loudspeaker with somewhat restricted performance characteristics. Both of these loudspeakers, as shown in the photographs of Figs. 12 and 13, use separately driven cones, a large cone for the reproduction of the low frequency range and a small cone for the reproduction of the high frequency range. The crossover frequency between the two cones is about 2000 cycles. The large voice coil, used to drive the large cone, exhibits sufficient inductance to adequately limit the current in the large cone in the high frequency region without the use of an auxiliary inductance. A condenser in series with the high frequency coil limits the current in the small voice coil in the low frequency region. The crossover network is shown in Fig. 10. The two cones are placed congruently so that in the overlap region the diaphragms vibrate as a single unit.

In the *RCA LC1A* mechanism separate magnets are used to energize the two air gaps. In the *RCA 515S1* mechanism a single magnet is used to energize the small and large air gaps. A magnetic bridge arrangement allocates the appropriate amount of flux to each of the air gaps. In the 515S1 mechanism the outside suspension of the small cone is fastened to the large cone. A mechanical network is used to prevent interaction between the two cones. The small cone does not vibrate at the low frequencies because the inner suspension is much stiffer than the outer suspension. In addition, the space between the cones is vented in the large cone to prevent coupling due to the compliance of this volume. In the *RCA LC1A* the large and small cones have independent suspensions.

There are many possible sources of distortion in a dynamic direct radiator loudspeaker. A few of the most common sources of distortion are as follows: The suspension system; small rigidity in the cone; non-homogeneity of the air gap flux; and inadequate flux density in the air gap. Every effort was made to develop a loudspeaker system in which these distortions would be as low as possible without adding unduly to the complexity of construction, the sensitivity, or the cost.

Cabinet

The cabinet shown in Fig. 14 has been found to be particularly suitable for the *RCA* Types LC1A and 515S1 mechanisms. The loudspeaker mechanisms are designed to be flush mounted with the face of the cabinet. Mounting the loudspeaker mechanism so that the front of the cone coincides with the face of the cabinet eliminates resonant and antiresonant effects which occur when there is a cavity in front of the mechanism. The cabinet is equipped with a port which may be used to accentuate the low frequency response if this type of characteristic is desired. The cabinet is lined with sound absorbing material, 1" thick, for the purpose of reducing standing wave systems within the cabinet which would react upon the loudspeaker and thereby produce a nonuniform response characteristic.

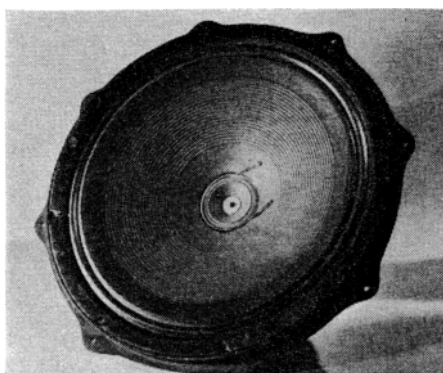


Figure 12: The RCA LC1A speaker mechanism.

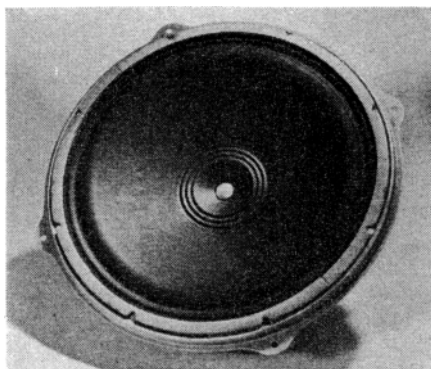


Figure 13: The RCA 515S1 speaker mechanism.

Loudspeaker Characteristics

The response frequency characteristics of the *RCA* LC1A loudspeaker mechanism, mounted in the cabinet of Fig. 14 and with the port opened and closed, is shown in Fig. 15B. It will be seen that uniform response can be obtained over the range from 40 to 15,000 cycles.

The directional characteristics of the *RCA* LC1A loudspeaker mechanism for the frequencies 500, 1000, 3000, 7000, 10,000 and 15,000 cycles are shown in Fig. 11A. The directivity patterns show that the angular spread for a variation of ± 3 db. is more than 90° up to 15,000 cycles.

The total r.m.s. distortion frequency characteristic for the LC1A loudspeaker for 1, 2, and 10 watts input is shown in Fig. 4B.

The response frequency characteristic of the 515S1 speaker mechanism mounted in the cabinet of Fig. 14 with port opened and closed are shown in Fig. 15A. The response is uniform from 50 to 12,000 cycles.

The directional characteristics of the *RCA* 515S1 loudspeaker mechanism for the frequencies 500, 1000, 2500, 5000, 7000, and 10,000 cycles are shown in Fig. 11B. The directivity patterns show that the angular spread for a variation of ± 3 db. is more than 60° up to 10,000 cycles.

The total r.m.s. distortion frequency characteristic for the 515S1 speaker for 1, 2, and 5 watts input is shown Fig. 4A.

Record Changer

A new changer and record of complementary design having a rotational speed of 45 r.p.m. has been developed¹⁷ and commercialized. This system provides a disc record and reproducer with wide frequency range, low noise, and low distortion characteristics. The records are $6\frac{7}{8}$ inches in diameter. Each record contains up to $5\frac{1}{3}$ minutes of playing time. The record changer will handle up to ten records.

The 9JY model of the new record changer is provided with a medium frequency range pickup designed for use with conventional radio receivers and phonographs. A wide range pickup cartridge has

¹⁷Carson, Burt and Reiskind; "RCA Review," Vol. 10, No. 2, page 173, 1949.

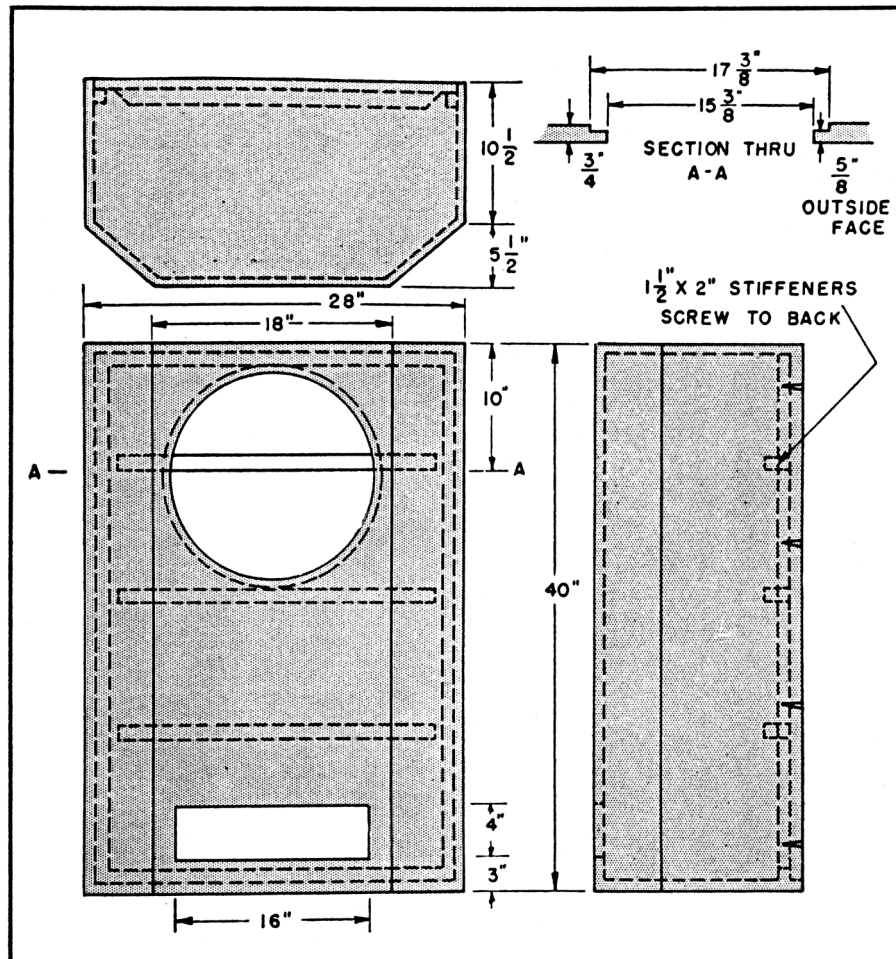


Figure 14: Front, plan, and side views of the cabinet for housing reproducing system.

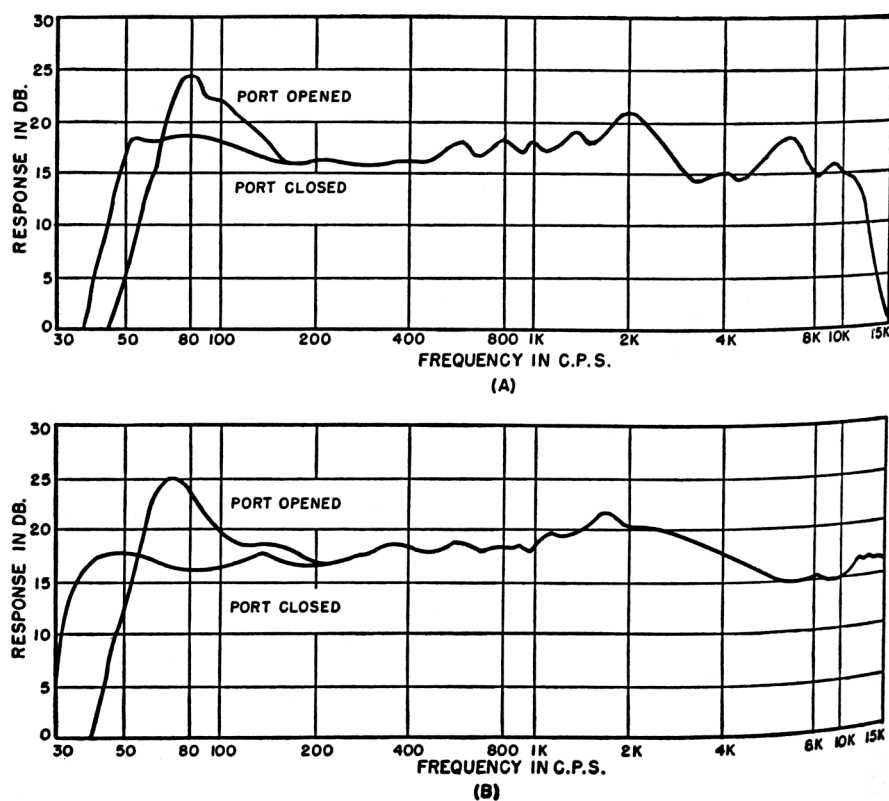


Figure 15: (A) Response frequency characteristics of the RCA 515S1 loudspeaker mechanism mounted in the cabinet (Fig. 14) with port opened and closed. (B) LC1A response.

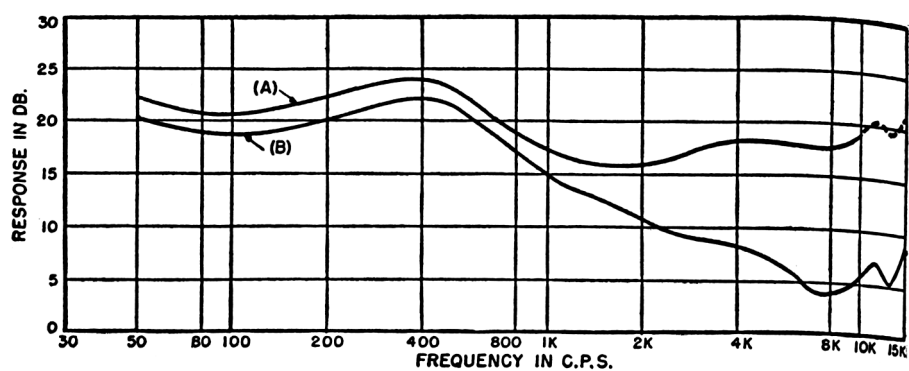


Figure 16: (A) Response frequency characteristics of the wide-range pickup combined with recording response frequency characteristic. (B) With a standard test record.

also been developed¹⁸ and may be substituted for the conventional pickup for wide frequency range reproduction.¹⁹ The response frequency characteristic of the wide range pickup using a standard test record²⁰ is shown in Fig. 16B. When playing the 45 r.p.m. records, it is necessary to consider the recording characteristics²⁰ used in making the records. Taking the recording characteristic into account the response frequency characteristic of the 45 r.p.m. record and the wide range pickup is shown in Fig. 16A.

Over All System

A photograph of the complete system, including the 9JY record changer, amplifier, *RCA* LC1A loudspeaker, and cabinet is shown in Fig. 1. In order to achieve accurate reproduction of the 45 r.p.m. records with the complete system, it is necessary to provide a small amount of frequency response compensation in the amplifier.

The potentiometer or volume control in the record player should be disconnected and the output of the crystal pickup connected directly to the amplifier through low capacity cable.

The needed compensation is achieved by resistors R_1 and R_2 in combination with condenser C_1 . For the LC1A loudspeaker R_1 and R_2 are each 510,000 ohms and C_1 is 50 μmfd . For the 515S1 loudspeaker R_1 and R_2 are each 270,000 ohms and C_1 is 300 μmfd .

Using the proper compensation the over-all response frequency characteristic of the system using the *RCA* LC1A loudspeaker is shown in Fig. 17 as is the over-all response frequency characteristic using the *RCA* 515S1 loudspeaker.

Tanglewood Demonstrations

The Festival Series of *RCA* radio, phonograph and television instruments (mentioned in Footnote 7)

¹⁸The wide range pickup cartridge RCA Stock No. 74625 was developed by A. D. Burt, RCA Victor Division of RCA.

¹⁹In order to realize the full high frequency response of the wide range cartridge, it is necessary to remove the volume control from the 9JY changer and to use the shortest possible length of low capacity cable between the cartridge and the amplifier.

²⁰Carson, Burt and Reiskind; "RCA Review," Figs. 12 and 11 respectively.

were first shown and demonstrated at Tanglewood, Massachusetts on July 29, 1947. In order to demonstrate the fidelity of these instruments, the reproduction of the instrument was compared with the full symphony orchestra. The Shed at Tanglewood in which the demonstration was conducted is an immense structure being 239 feet in length, 200 feet in width at the rear, and 40 feet in height. The microphones for recording the sound were located at the front of the stage. When the recording was made, the sound level was measured in various portions of the Shed, so that the level of the reproduced sound would match the sound produced by the orchestra. A record was made of a piece played by the Boston Symphony Orchestra. Twelve *RCA* LC1A loudspeakers, placed at the front of the stage, were used to reproduce the orchestra. In the demonstration, the Boston Symphony Orchestra played the first portion of the selection and then, suddenly the switch to the record was made without interruption in the music and the remainder of the selection was reproduced. Dozens of music critics from several large cities stated in their newspaper and magazine columns that it was scarcely apparent where the live orchestra left off and the reproduced music began. This was due to the fact that the instruments reproduced both the tonal and volume ranges of the orchestra. The frequency range of reproduction was 30 to 15,000 cycles. With the twelve *RCA* LC1A loudspeakers, these tests showed that it was possible to duplicate the frequency and volume ranges of the orchestra.

New Speaker Model

Since the preparation of this article, continued engineering work on the application of the duo-cone principle has resulted in improvements in the design and manufacture of duo-cone speakers. A new model, the *RCA* 515S2, incorporating these improvements has been announced recently by the Tube Department of *Radio Corporation of America*. The amplifier and compensation for the *RCA* duo-cone loudspeaker 515S1 described in this article also applies to the *RCA* duo-cone loudspeaker 515S2.

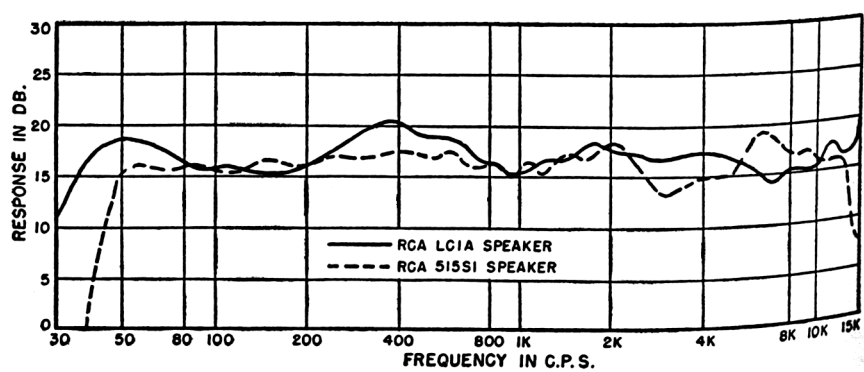


Figure 17: Over-all response frequency characteristic of systems using the LC1A and 515S1.