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Design Elements for Improved Bass Response in Loudspeaker Systems

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A frank discussion of the factors which influence the reproduction of low frequencies, and a description of means which may be employed to increase bass radiation.

It has been said that music is the only form of dissipation which may be engaged in to any degree by the individual without harm to his physical well being.

Recognition of this postulate helps to explain the accelerating interest in quality sound reproduction as evidenced by the growing ranks of high-fidelity enthusiasts. This enthusiasm constitutes a profitable market for the manufacturer. Accordingly, acoustic research has been spurred recently to satisfy this demand. The listening public, lacking the objectivity of the engineer, has found it difficult to articulate its needs, thus making it hard for the engineer to direct his efforts with any degree of certainty towards a problem the solution of which is primarily subjective. As in the formative stages of any art, much of what has been accomplished in high-fidelity reproduction was through trial and error methods. Exploratory tests conducted by two well-known audio authorities may suggest the objective criteria so necessary to the engineer, and disclose some important points which previously have been overlooked by the lay listener. It is the purpose in what follows to indicate that the incorporation *of improved bass response in reproduced sound is probably the most important step* in the further development of the art.

Listener Reaction Tests

Howard Chinn of CBS conducted a series of listener tests using reproduced music. The general conclusion from this test was that listeners prefer a narrow, or at least a restricted band of frequencies.

This conclusion violated every aim of the idealist who instinctively believed his goal to be duplication of reality—including the reproduction of all frequencies between 16 and 16,000 cps.

In refutation of the previous test conclusions, Olson of RCA employed a live orchestra with acoustic low-pass filters to test listener range preference. *The choice was incontrovertibly for the widest range response possible.* The discrepancy in test results was shown to be principally the result of odd-order distortions introduced by the electro-acoustical system. Narrow band reproduction subdued this distortion, making the sound more tolerable.

An Indicated New Approach—The rather conclusive tests by Olson show that the frequencies from 16 to 16,000 cps are necessary for ultimate listening. A concomitant conclusion is that the widest frequency range must be accompanied by very low odd-order distortion or the band must be restricted to be tolerated.

This last compromise cannot be reconciled by the progressive electro-acoustic engineer or he denies his reason for being. For sometime he has had virtually perfect wide-range reproduction in the laboratory, and has awaited only sufficient arguments to warrant presenting it to the public. The way to this presentation is paved by these facts:

1. *Public Acceptance*—The determination that the public desires high quality sound reproduction has been made. Note that this desire includes all the audible frequencies without balance from the bass range.
2. *Wide-Range Source Material*—New wide-range microphones, low distortion amplifiers, vinylite records, and magnetic tape will allow the wide-range speaker system to perform, sources no longer being a limiting factor.
3. *Treble Driver Units*—High-frequency driver units linear to 10,000 cps with less than 2 per cent harmonic distortion are available. "Super" high frequency drivers linear to 17,000 cps are obtainable. These are designed to supplement the average high-frequency driver.
4. *Low Speaker-System Distortion*—The principle of separating the driver units for reproducing only their respective portions of the spectrum reduces the transducer distortion to the region of acceptable limits.

The notable exception to the listing above is adequate bass in the reproducer response. The goal of good listening in the home cannot be achieved without full consideration being given to the reproduction of the first three octaves up to 130 cps.

Consider for a moment that at 50 cps, a quarter wavelength is 80 in. In order to reproduce down to this frequency only, *just slightly below the third oc-*

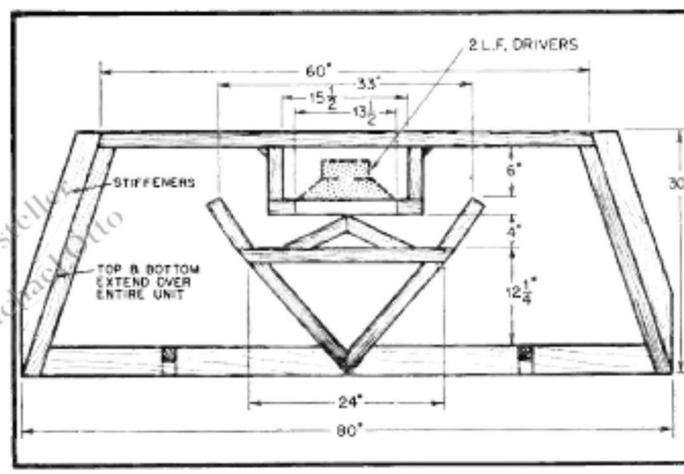

Fig. 4. Cross-section of theatre-type folded horn—the C-5 "bin."

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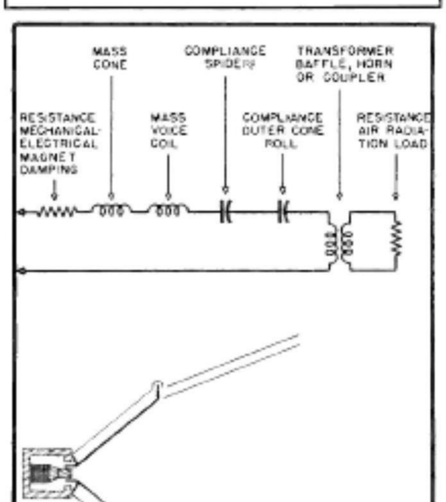


Fig. 1. Typical loudspeaker and its equivalent circuit for investigation of design requirements.

tave, a horn 80 in. across the mouth is necessary. Thus, the usual claim of response to 40 cps would appear specious, to say the least, much less the sometimes added phrase of "useable response to 20 cps."

Further need for better bass response lies in the fact that the system is generally called upon to reproduce program music in the home at a much lower level than that at which it was originally recorded. Reference to the ear sensitivity curves of Fletcher and Munson show that the usual playback level of around 80 db leaves the bass attenuated by about 20 db. The best commercial amplifiers seldom incorporate more than 12 or 15 db of bass boost, for this equalization is costly of final overall power output, especially at the extremely low frequencies where the amplifier ordinarily finds some difficulty in meeting its specifications.

It can be incontrovertibly shown that good extreme bass response is necessary for music reproduction, even though the particular fundamentals involved are not included in the passages being reproduced.

This is explained through the fact that music consists to a very large degree of transient signals which seldom approach a steady state. Thus, staccato passages on a flute with a fundamental of 500 cps will not be reproduced with the proper envelope shape if the low-frequency interruptions of the fundamental tone are below the pass band of the speaker system. Moreover, the mathematics involved will show that for perfect reproduction of this same staccato flute passage the band should be *infinitely* low *and* high. For practical purposes, however, it can be assumed that distortion will be minimized, even on narrow band sources, if the pass band of the speaker is as wide as possible.

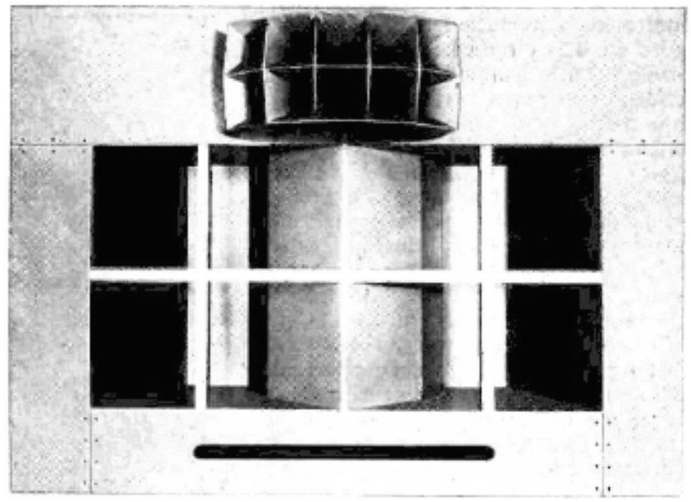


Fig. 5. Front view of typical folded horn.

It has been previously concluded that the widest reproducing range is important, and it may be assumed that the extreme low end of the spectrum in reproduced sound has been neglected. It is remarkable in view of the obvious and overwhelming importance of these low frequencies that so little has been done to accomplish this reproduction.

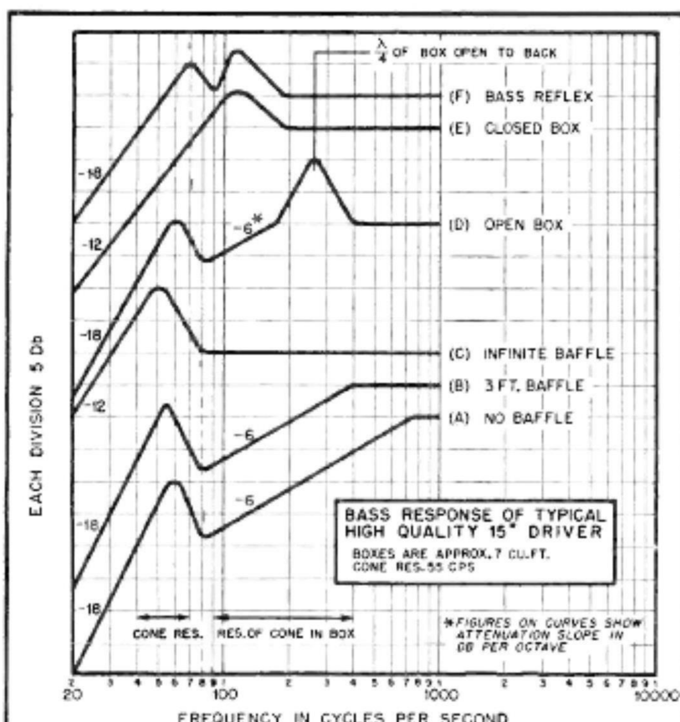
It is the purpose of the balance of this writing to disclose what *can* be done, and perhaps to point the way to the complete accomplishment of adequate bass.

The Reproducing System

A proper understanding of the reproducing system cannot be achieved unless we consider the elements with which we have to work. In Fig. 1, we observe these elements and the equivalent electrical circuit. For best comprehension of what is to follow let us discuss the items shown in the circuit one by one.

(1) Magnet Damping (Mechanical-Electrical Resistance)—In an electrical circuit, resistance will lower the "*Q*" and broaden the transmission band. Exactly the same thing transpires in the acoustic circuit. High magnetic damping results in fine broad band efficiency and subdues the natural modes of the vibratory system. There are other forms of damping which could be grouped along with this item. For instance, a shorted turn in the voice coil would provide this same sort of smoothing action, but at the expense of efficiency. Low internal impedance in the associated amplifier is of great value in providing this desirable damping action and accomplishes this without lowering overall speaker efficiencies.

(2) Mass of the Voice Coil—A short analysis of the equivalent circuit will disclose that voice coil weight becomes



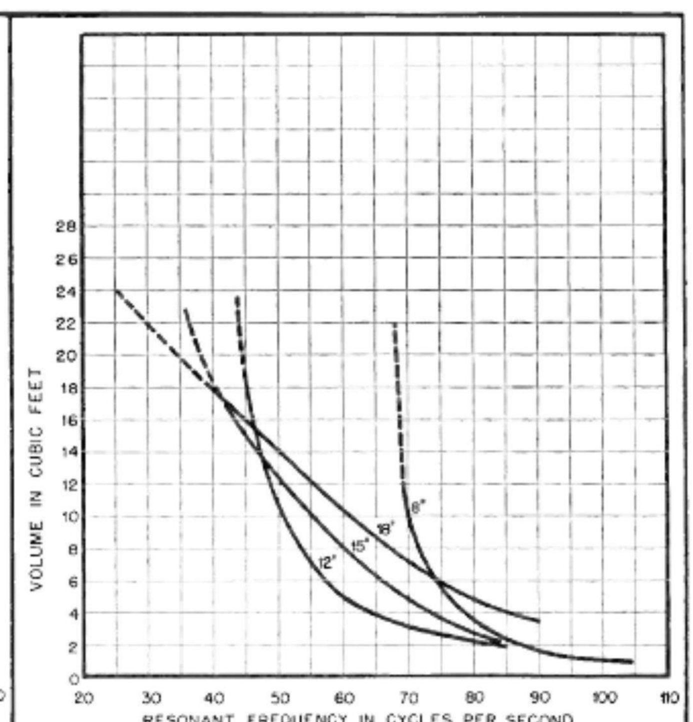


Fig. 2 (left). Comparison low-end response obtainable from various types of speaker mountings. Fig. 3 (right) Optimum size of speaker enclosure for speakers of various diameters and resonant frequencies.

increasingly important as the frequency goes up. The circuit becomes mass controlled, with compliances having less effect. Copper wire is used universally in low-frequency drivers because of increased conductivity irrespective of the weight disparity between it and aluminum. The higher resistance of aluminum is a disadvantage at low-frequencies, whereas, above 1000 cps the lighter mass offsets the disadvantage by a factor of some 35 per cent. At low frequencies, the mass of the cone and air load is little affected proportionately by the addition of 5 or 6 grams, due to the copper, with its attribute of high current capacity. It is in the extreme bass range that the current assumes high proportions. At 15 watts input, the current at 50 cps is on the order of 2 amperes in the voice coil.

(3) Cone Mass—Observation of the inductive element represented by the cone mass will lead the electrical theorist to assume that increasing the cone weight will lower the resonance and increase the bass range. This is correct, but an increase in cone weight of double the usual 25 grams will lower the resonance by only a few cps and decrease the efficiency by over 75 per cent. In a driver of top design using 5 lbs. of Alnico V, the iron of the structure is working at its economical limit, and this loss of efficiency cannot be made up in any practical way.

(4) Compliance—The next point of attack is logically the suspension system or capacitive element. The usual low-frequency driver has fairly stiff outer compliance rolls, as well as a stiff inner suspension, or spider. The reasons for this are quite practical. The resonance will naturally become lower if the compliances are increased. But here the manufacturer is faced with another dilemma. If he incorporates low compliances, the cone without adequate air loading will "bottom." This is caused by the voice coil hitting the flange on the nosepiece. In addition, non-linear response will ensue because of lack of restoring force when the voice coil rides out of the area of uniformly dense flux. A 30-watt rating for a driver becomes less than 3 watts when the suspensions are made more compliant without proportionately increasing the air load. But this, along with increased air loading, points the direction towards increased bass range and efficiency.

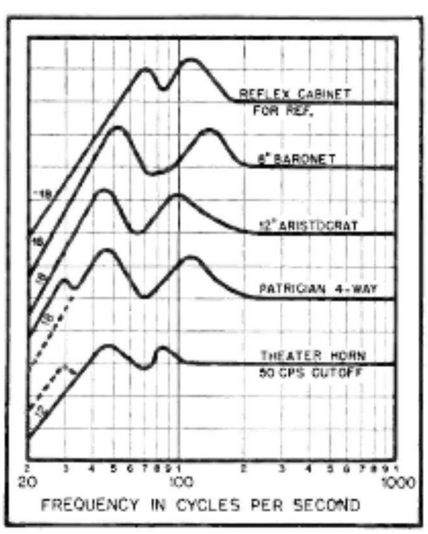


Fig. 6. Typical response curves of reflexed cabinet, several manufactured enclosures, and the folded horn.

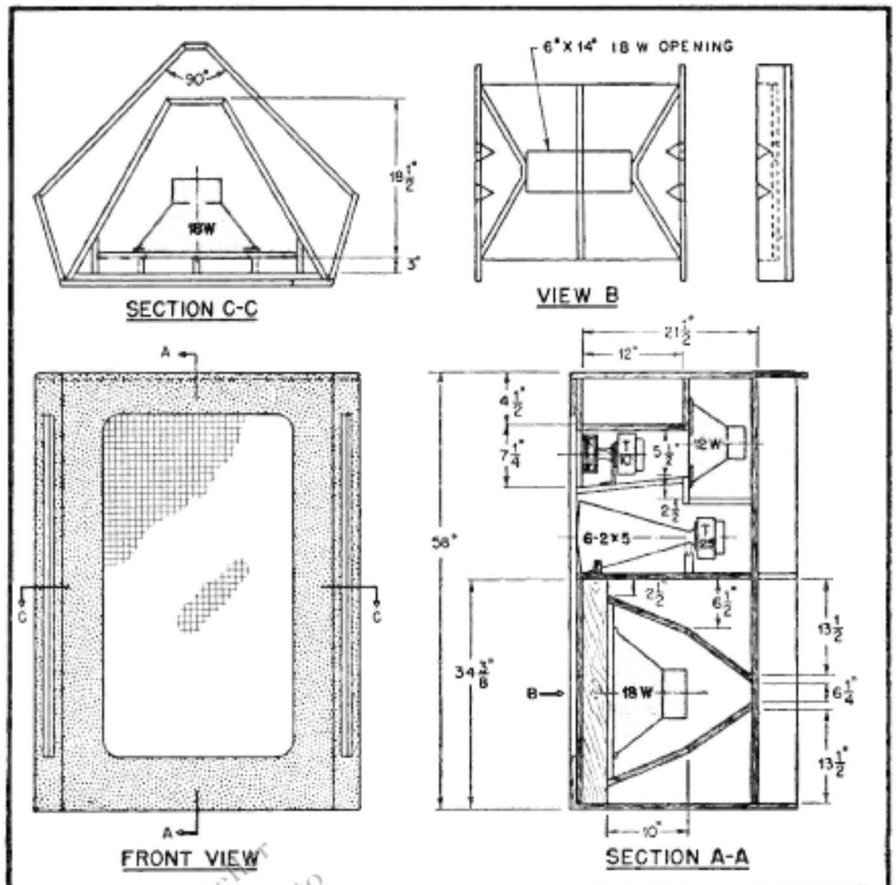


Fig. 7. Simplified constructional drawings for the "Patrician" four-way system.

The average good 15-in. low-frequency driver has a free resonance of about 50 to 75 cps. Increasing the compliances reduces this resonance to about 35–50 cps. One 18 in. low-frequency driver on the market has a resonance guaranteed below 30 cps.

(5) The Acoustic Transformer—(4) above suggests that the operation of a driver unit cannot be treated on without consideration of its acoustic load. This load of very low impedance, i.e., the open air, must be coupled to the region of cone movement, an area of very high acoustic impedance. Considering the size of the wavelengths to be reproduced, we find that the "transformer" must deal in large surfaces and volumes. Hence, we must work with a baffle, box, and horn concept which is fundamentally architectural in nature. With no baffle at all a 15-in. speaker will begin to lose level from 800 cps down at the rate of 6 db per octave, as shown in curve (A), *Fig.* 2. This is due to the "doublet" effect of a dual radiator, for as the wavelength approaches the diameter of the cone, cancellation occurs because of the out-of-phase condition.

The Small Flat Baffle

Curve (B) represents a driver on a small baffle. Note that the "doublet" action takes place at a lower frequency, determined once more by the wavelength of the frequency being reproduced and its size relationship to the diameter of the flat surface.

The Infinite Baffle

Continued increase in the size of the baffle involves another factor, however. If the baffle is large enough, or infinite, so that the critical frequency or wavelength of the diameter corresponds to the mechanical resonance of the driver, range response is extended to cone resonance, as shown in curve (C). But past the critical resonant wavelength of the driver cone, attenuation takes place at the rate of 12 db per octave, regardless of the size of the baffle. This is due to the stiffness, or low capacitive effect, of the driver cone mechanism, and indicates the value of a driver with low free-space resonance. From the practical aspect, it can be assumed that an 8-in. speaker with a free-space cone resonance of 62 cps will not benefit with a baffle larger than 5 feet in diameter.

The Open-Back Box

Operating like the infinite baffle when the proportions are large, the open box is quite adequate provided that the dimensions prevent cancellation of the front by the back wave. However, in the usual dimensions suitable for a living room, say 6 to 12 cubic feet, the resonance of the box itself causes a violent peak of perhaps 10 to 17 db around 175

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IMPROVED BASS RESPONSE

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cps, resulting in a disagreeable boominess characteristic of commercial radio sets, juke-boxes and the like. As shown in curve (D), attenuation below resonance is at the usual rate of 12 db per octave plus 6 db per octave due to the "doublet" or phasing out effect of the back radiation. In general, any open-back box is considerably improved by closing off the rear.

The Enclosed Box

The simplest form of good speaker enclosure is the enclosed box, with the only energy radiated into the listening area being from the front, as in the case of the infinite baffle. The chief difference between this enclosure and the infinite baffle is that the capacitive load on the back of the cone increases the stiffness of the suspension system, raising the mechanical resonance. This causes the usual attenuation of 12 db per octave to start at a higher frequency. Curve (E) shows that the level just before attenuation is higher, or peaked. This is true because the cone mass is resonating with the low compliant mass within the cabinet. When this peak is objectionably high, holes, or acoustic resistances in the back side of the cabinet will lower the peak, and consequently extend the bass range with another smaller peak before violent attenuation sets in.

Reflections with attendant reinforcements and cancellations within the box occur from about the fourth or fifth octave on up. These can be minimized with sound absorbent material generously applied to opposing surfaces.

Reflex Boxes

The currently popular vented enclosure utilizes a novel method of raising efficiencies in the last part of the 3rd octave around 100–130 cps. The front port, or vent, is tuned to allow for a delay of the back radiation. This permits an in-phase relationship resulting in a reinforcement just below the peak caused by resonance of the cone in conjunction with the true box resonance. Curve (F) indicates results to be expected with enclosures of the same relative size, approximately 7 cubic feet. Observe that attenuation past resonance is 18 db per octave versus 12 db per octave in the completely closed box. All other factors being equal, the range is not as great as the closed box. The peaks are higher and the valleys lower. Moreover, the characteristic boominess is objectionable to the discerning listener. But the fact remains that the added efficiency, in the more restricted spectrum that it does reproduce, finds considerable favor.

It is recommended as a guide that no less than 6 cubic feet be considered for satisfactory results. The depth of the box should be about one-half the length or height. Although formulas exist for computing the port size, the necessary data on cone weights, compliance, cone resonance, and other parameters are seldom available to the constructor. The most practical and by far the most accurate method of determining optimum port size in a specific box for a particular speaker is the procedure as follows:

Place a voltmeter across the voice coil and start with a port of about 150 square inches. Scan the first three octaves with an audio oscillator playing through the speaker system, gradually decreasing the port size until two peaks are observed in the reading of the highest intensities and at the lowest frequencies possible.

As a guide to the optimum box size for top results with a speaker of given diameter, see *Fig.* 3. Note that for the best results—insofar as extended bass reproduction is concerned in a medium size cabinet, (say up to 12 cubic feet)—the 12-in. cone has a considerable edge over the 15-in. model. The low-frequency driver of 18 in. is impractical and almost unuseable unless the volumetric capacity of the box is very large, or over 20 cubic feet.

Recapitulation

A study of the comparative designs offered above suggests that a rather poor job of bass reproduction is being effected unless large cavities, of the order of 12 cubic feet on up, are considered. The infinite baffle, combined with a cone resonance of 40–45 cps, does by far the best job if it is feasible to employ it. The vented box lends a "muddy" quality to the music and restricts the range, but is generally preferred over the plain closed box of equal size in spite of the added purity and extended range of the latter. This can be explained by reason of the foremost requirement of efficiency for the bass, even if of more restricted range.

Of the utmost importance in any of the designs above is low cone resonance, which also involves high compliances, or values of C in the equivalent circuit.

Towards Better Bass Response

Theater Horns—With space not being a limiting factor, the folded theater horn, is preferred. Response with this almost ideal enclosure is flat to 50 cps. Below this point, attenuation is fairly rapid. However, this horn delivers the smoothest, distortion-free response down to 50 cps that the art has been able to develop. The difficulty presented otherwise by this system is the need for dual drivers, and the requirement for a rather expensive cellular horn and treble driver above 400 cps. Observe the very low portion of the curve for this unit, shown in *Fig.* 6 with the curves of a number of commercial enclosures. This curve shows what can be done by enclosing the backs of the drivers with a cavity of about 16,000 cu. in. If the Klipsch-type units with high compliances are employed, it is possible to resonate this back cavity with the frontal air load mass and achieve added response down to 30 cps.

The vast majority of living rooms, however, have no provision for a system approaching the size of this rather ungainly device. The basic principles can be adapted, however, as disclosed in the more practical enclosures to follow.

Corner Designs

As a rule folded horns are recommended for operation only up to 400 cps. At almost 500 cps and up, the higher frequencies find difficulty in following the circuitous path, *unless supplemented by front radiation* from the bass driver cone.

In several E-V designs, the folded horn loading is actuated from the rear of the cone while radiation of the higher frequencies takes place equally from the front. The important cavity directly behind the cone acts as an acoustic low-pass filter below 200 cps. This filter prevents phasing out of the front radiation by the back waves above this point. Some interference is measurable below 200 cps, but the generally smooth response to 65 cps overwhelmingly justifies the design. The sides of the room provide additional loading, acting as an extension of the mouth of the horn. This assists further in the formation of a spherical wave shape which promotes easy listening. Some radiation is effected, just barely useable, at 30 to 45 cps. The corner design proves itself an excellent substitute for the C-5 bin where the larger space required is not available.

Completely Horn Loaded Corner Design

The "Patrician" 4-way system employs a fully horn-loaded driver for utmost purity and efficiency, as shown in *Fig. 7*. In addition, the feature of resonating the back cavity with the front air load mass is utilized. The complete assembly is slightly less than 30-in. deep, allowing it to pass through a standard door.

To insure optimum results the bass horn design is slanted towards the lowest part of the spectrum, and a crossover at 220 cps transfers the task of reproducing the 200–600 cps range to a 12-in. low-frequency unit with an independent horn. To maintain optimum throat-to-mouth relationships, part of the face of each driver is masked off to the proper size. Closing down these throats effects attenuation only of the higher frequencies, well beyond the pass band of these two units. From 600 to 3500 cps, the treble driver exhausts through the large 2 × 5 horn. High-end attenuation for this unit is only 6 db per octave above 3500 cps. This allows a reinforcement in combination with the small Model T-10 super-tweeter of the critical 5000-cps band which so vitally effects the "presence" quality. Dramatic increase in total apparent efficiency is achieved with a 4 to 6 db rise at this particular point. The T-10 Sonax Driver carries the high end through 16,000 cps.

The back cavity of the large driver comprises some 8000 cu. in. to match the high compliance of the 18-in. cone. Note that the small triangular cavities, four in all, are fed to the larger area behind the cone by notches. This makes use of all the space in the bass section. It is essential that the back cavity be absolutely airtight. Horn assemblies are tested in production with a pressure gauge for leaks. The equivalent of a ½" hole will raise the lowest radiation peak by almost 5 cps. Moreover, the driver itself is sealed from front to back with a solid dome, incorporating no "breather."

The impedance characteristic of a loudspeaker rises at the extremes of the spectrum. To more nearly match a 16-ohm crossover network at the very low frequencies, the special Klipsch-type driver has a d.c. voice-coil resistance of only 3.2 ohms, as opposed to the usual resistance of 11.6 ohms in a more conventional unit.

In listening to this system some rather startling effects are observed. When live tape is used as a source, it is possible for the spatial effect of the recording locale to be unconsciously evaluated, contributing materially to the illusion of reality. This is effected through the reproduction of extreme low-frequency effects, such as very low room noises and air rumble, more frequently felt rather than heard. Because all four drivers are loaded with columns of air, diaphragm excursions are held to a minimum, assuring high damping of the voice coils in the densest flux areas, and the smaller excursions minimize diaphragm breakup. Perhaps the most important observation is a negative one—the lessening of listener fatigue. This contribution may be ascribed principally to the elimination of harmonic distortion through the multiple division of the spectrum by disparate drivers.

Summary

Bass response in currently available loudspeaker systems and enclosures is poor. By considering the spatial requirements and utilizing the corner of the room as an extension of the necessary air-load on the driver cone a considerable improvement in bass range and efficiency can be achieved.

Though the foregoing offers no complete solution to the perfect reproduction of the first three bass octaves, it is felt that perhaps an important improvement of at least 100 per cent is offered from the standpoint of range extension. Efficiencies are improved greatly.

Improvements resulting from the horn load are an appreciable decrease in diaphragm excursions, with correspondingly greater power handling capacity of the driver, decreased intermodulation distortion, and vastly improved transient response.

Subjectively, it is found that apparent gains in realistic reproduction are considerably greater than the bare mathematics would indicate. The masking effect of the more adequate bass prevents extended high response from seeming shrill and thin. The resulting tonal balance achieves a more adequate feeling of listening satisfaction.