A Semicircular Exponential Horn

One answer to limitations in bass response

REUBEN M. CARES, M.D.*

One answer to the limitations in bass response is arrived at by a serious experimenter who analyzed all the literature on the complicated subject of horns and other accepted methods of achieving satisfactory reproduction and then used his head to work out a horn structure which solved his requirements.

RESONANT CHAMBERS are essential to all musical instruments, whether stringed, woodwind, brass or of percussion type. Music in the lower registers and "bottom bass" depends on three familiar forms of transducers. Thus the bass viol or cello has a body with a vented enclosure resembling a bass reflex cabinet for speakers. Brass and wood-winds are all actuated by some type of horn-loading of the sound source—vibrating lip or reeds. The tympani enclose air cavities of large volume, as duplicated by speaker enclosures of infinite baffle type.

The lower the register of a musical instrument, the larger must be the enclosed air column or mass coupled to the sound source. A woofer-enclosure usually differs in that one desires a wider frequency range than its musical counterpart, plus higher dynamic levels. The most vigorous fortissimo from the bass viol can hardly approach the loudness of a 30-watt amplifier speaker system at rated output capable of reproducing the instrument's pitch and timbre. The problem is that of undistorted reproduction of bass within the energy range of the audio system.

The appraisal of various speakers and their enclosures as regards low-frequency response is ultimately subjective. Musical tastes, auditory acuity[1] and volume-level preference, other things being equal, comprise a greater number of variables than may be accommodated by established electro-acoustic standards.

This physiologic principle applies not only to speakers and enclosures, but also to listening evaluation of amplifiers which are identical electronically. McProud[2] called attention to this puzzling phenomenon in a detailed review of amplifier design. Identical series of laboratory bench measurements of two well-designed amplifiers will give different results in a listening test. As emphasized by McProud, we don't know yet how to measure certain characteristics which are subjective and of indefinable aesthetic values.

Listening tests thus depend not only on electronic parameters but also on the imponderables of psycho-acoustic phenomena. This accounts for the public acceptance of a multiplicity of designs in commercial and custom-built enclosures. Regardless of standard acoustic formulas, considerable deviation from ideal speaker-enclosure design will still appeal to some segment of the critical listening public. This exists since conditions beyond control of the manufacturer or audio engineer include acceptable costs (a matter of cultural indoctrination), room acoustics, and most important, the degree of auditory and musical discrimination of the consumer.

Present convention (implying domestic restraint or other home influence) dictates, except for the very well-heeled minority, that an audio system, including the speaker enclosure, should be housed in a cabinet which has, at the most, the bulk of a desk or buffet. Any piece of electronic cabinetry larger than this 25–30 cubic foot size in the average living room disturbs a balance in room furnishing in the average American home.

This arbitrary limit in size is a question of mores. A natural musical instrument is tolerated with no undue regard for its size. The permanent presence of a piano is rarely challenged even in a grand size. Fortunately, the prestige attached to this single large household instrument is gradually being applied to high-fidelity units. One limitation to home music systems still applies—that the large volume be unobtrusive. The larger the system, the more disguise is used—as built-in shelving, corner cabinetry, and the like.

Problems of Speaker Enclosure Choice

The three main types of air chambers for bass range—vented boxes, closed chambers, and horns—are present in numerous modifications of speaker-enclosures. Of these, Plach and Williams[3]

TABLE I

ACOUSTIC ANALOGIES OF INSTRUMENTS OF LOWER REGISTER TO SPEAKER ENCLOSURES

Instrument	Audio Spectrum Kcps.	Resonant Chamber	Horn Type	Mouthpiece (Spkr. Chamber)	Throat	Air Column	Mouth (Bell)
CLARINET (Boehm)	.15-14	HORN	CONE (cyl.)	CONICAL	1"	20"	2"
TRUMPET	.18-11	HORN	CONE	HEMISPHERICAL CUP	¼"	8'	6"
FRENCH HORN	.09-8	HORN	EXPONENTIAL	CONICAL	½"	9-18'	15"
TROMBONE	.08-8	HORN	CONICAL	CONICAL	⅜"	9-13'	7"
TUBA	.04-7	HORN	EXPONENTIAL	CONICAL	½"	14'	24"
CELLO	.06-8	VENTED BOX					
BASS VIOL	.04-9	VENTED BOX					
TYMPANI	.042-9	INFINITE BAFFLE					
ORGAN (Church)	.016-12	OPEN PIPE	CYLINDER				

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* *Director of Laboratories and Chairman of Audio-Visual Committee, Kings Park State Hospital, Kings Park, N. Y.*

[1] As with visual focussing accommodation which decreases steadily above middle age, the audible frequency range decreases with age. At 20 years many can hear to 20,000 cps or higher. After middle age few people can hear beyond 14 or 15 kcps.

[2] C. G. McProud, "Amplifiers and Preamplifiers." AUDIO, January, 1955, p. 23.

[3] D. J. Plach and P. B. Williams, "Horn-loaded loudspeakers." *Radio and Television News*, May, 1952.

TABLE II

LOW-FREQUENCY EXPONENTIAL HORNS

Cutoff cps	Wave-length λ feet	Area Doubles $S_x^2 = 2S_1^2$ inches	Flare Rate m*	Throat Diameter 2% of λ inches	Path Length ½λ feet	Mouth Diameter ¼λ** feet
200	5.6	3.84	.176	1.3	2.8	1.4
100	11.2	7.68	.088	2.6	5.6	2.8
50	22.4	15.37	.044	5.2	11.2	5.6
25	44.8	30.75	.022	10.4	22.4	11.2

* Flare rate is sufficiently gradual to approach a conical horn and thus allow extended lengths of straight wall sections.

** Within reasonable limits, circumference of any polyhedral opening may equal a wavelength; minimum diameter is 1/16 wavelength to avoid waveform distortion.

Exponential formula — $S_x = S_1 e^{mx}$

among many others, have indicated that properly designed horn-loading gives the best performance and output for bass reproduction, particularly in the critical 30–100 cps range.

No other audio-visual component of well-designed home music systems approaches the physical space requirements of speaker enclosures. The need for extended sound paths in the acoustic horn-loaded devices without undue bulk has been fairly well met by a "telescoping" compression of the horn by the folded horn principle. Even more bulk or space-enclosure is needed with infinite baffles. The folded-horn, obviously, does not physically duplicate the configuration of lowest register instruments. The latter require dimensions and construction universally standardized to avoid structural deviations that will alter the pitch, timbre, and tone range. The size and shape of the mouthpiece, the continuous air column in *smooth curved* shapes and the bell or acoustic mouth have mutually dependent specifications. With any noticeable change in the design of a trombone, for example, a new instrument is born—subject to musical acceptance or rejection.

Table I compares speaker-coupled chambers to enclosures which form part of bass musical instruments. For use with speakers, the horn is most adaptable since it can be altered in its throat, path or mouth dimensions to allow for any desired acoustic impedance. Souther[4] found in comparative studies that low-frequency response curves for resonant chambers were increasingly efficient in this order—flat baffles, enclosed boxes, vented boxes, and horns. Below 100 cps, he felt that a minimum of 12 cubic feet of enclosed air is needed in any chamber.

Some Features of Horn Acoustics

According to Olsen[5] "A horn is an acoustic transducer of varying cross-sectional areas capable of presenting any value of acoustic impedance to the sound generator." Plach and Williams had, in another study,[6] defined a horn as "a device that presents to the speaker a complex load consisting of a useful resistive component acting for acoustic radiation and a quadrature component which is mass-like or inductive in nature."

As early as 1816[7] it was demonstrated in analysis of brass instruments that the shape of the horn—hyperbolic, parabolic, or conical—determined the pitch. Horns for music have existed since biblical times. The facility in modifying the register, timbre, volume, and frequency range have inspired innumerable forms of horns for centuries.

The authoritative Grove's Dictionary of Music decades ago noted that changes in pitch were long recognized following modifications of the mouth area, air column, and even the throat (mouthpiece). Musicians have habitually used the hand to stop the bell or mouth of horn instruments to flatten the pitch. This, according to Grove, (without benefit of modern wave-form studies), is due to an "inharmonic series of tones." The size and shape of the mouthpiece and throat of a wind instrument govern largely the characteristic fundamental and harmonic tones. The pronounced suppression of fundamentals in a violin or cello by the use of a tiny mute on the bridge is a physical damping effect known long before electro-acoustic damping.

The importance of the length of a horn has been known for centuries. Giant straight horns, roughly conical or exponential, have been in outdoor use for hundreds of years among the mountaineers of Switzerland, South America, and the Himalayan Mountains for literal peak-to-peak voice communication over miles-wide distances. The wooden Swiss Alpenhorn runs to eight feet in length and even more.

Compared to the cylindrical flute or clarinet, brass instruments with horn shapes are capable of yielding a larger number of partial tones; i. e., intermediate low-frequencies. This is what engineers strive for in audio systems utilizing in acoustic formulas the empirical experience of musicians of the past.

One additional significant feature is that increased blowing or overblowing of any musical horn will cause an increase in the number of harmonic tones. By analogy, a speaker horn enclosure heard at a 1-watt output may not have the same profile of fundamental and harmonic combined tones as at 20- or 30-watt output. This may account for variable listener acceptance of an audio system where volume settings are changed for individual preference. The different combinations of harmonics are hard to measure since many oscilloscopes will not manifest much less than a sizeable 3 per cent harmonic distortion of the complex wave forms. The trained ear appears to be more sensitive or discriminatory.

The semicircular exponential horn enclosure as part of the author's music unit. It is detached to avoid acoustic feedback. Behind left and right grill-drawer compartments are phono and professional tape deck. Center top grill conceals separate TV speaker in a ventilator shaft, and tuner front end controls a remote third speaker. Built-in desk balances speaker enclosure. The center section and speaker horn enclosure are on casters and roll out for maintenance. Subassembly of desk, and left and right halves of shelves are screwed and dry-doweled for ready disassembly of entire unit for possible future reinstallation. *Unit constructed by Fred Nelson, Kings Park, N. Y.*

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[4] H. T. Souther, "Design elements for improved bass response in loudspeaker systems." AUDIO ENGINEERING, May, 1951.

[5] H. F. Olsen, *Elements of Acoustic Engineering*, Van Nostrand, 1938.

[6] D. J. Plach and P. B. Williams, "Loudspeaker enclosures." AUDIO ENGINEERING, July, 1951.

[7] *Encyclopedia Britannica, 11th Ed., 13:* 691. New York University Press, 1910.

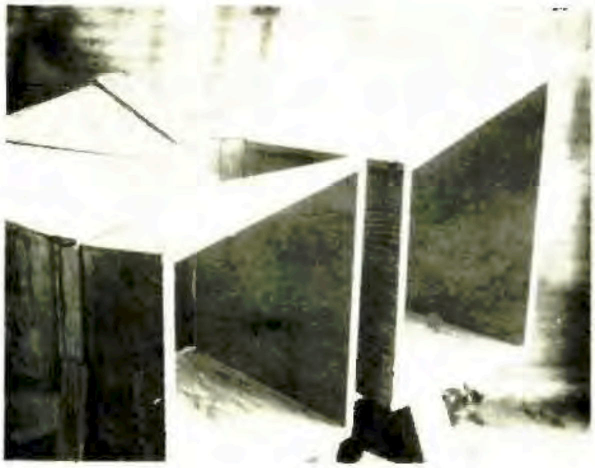

Fig. 1. The semicircular horn before enclosing it in another speaker cabinet. The left orifice is for a 15-in. speaker, tapering to join a 100-sq.-in. throat; the right opening is the mouth of the horn.

Limitations to True Bass Response

A. In the Speaker-Amplifier System

(1) *Damping*

Clements' detailed analysis on damping effects[8] showed that horn-loading is one solution to unavoidable attenuation of low frequencies which occurs with high amplifier damping factors. The latter amplifier feature may effect as much as a 10-db loss in speaker cones with heavy magnets, resonant at or below 60 cps according to this observer. This over-damping may be offset by matched horn-loading as well as by the recent methods of adjustable feed-back or variable internal amplifier impedance. However, the additional voice-coil damping by a powerful speaker magnet remains unaffected.

The bass-reflex cabinet for speaker loading gives too sharp a phase reinforcement at cone resonance and requires debatable amounts of internal padding. A closed box for infinite baffle effect must be quite large in volume and still will tend to restrict its bass loading to a narrow band in the audio spectrum.

In reviewing the merits of inverse feedback amplifiers, Childs[9] felt that all three desirables—perfect damping, perfect transient response, and sustained flat output at the bass end—are impossible to obtain simultaneously. Mutually antagonistic forces exist in the electronic and mechanical circuits of the amplifier-woofer-enclosure complex. Cone-to-air acoustic impedance coupling, which varies inversely with frequency, can produce spurious cone excursions thereby degrading the general response. For this reason horn-loading is most adaptable for critical coupling to a given system since any degree of acoustic impedance can be tailor-made. Mouth, throat, flare rate, and horn path can all be designed for fairly predictable acoustic behavior.

(2) *Speaker Design*

Bass reproduction by a speaker requires high current and a low voice-coil mass. At 50 cps a woofer will consume as much as a 2 amp. current in the voice coil at 15-watts input. There is a geometrical rise in current requirements the lower the frequency one reaches. One can double the cone mass to extend the bass end, but the small increment is offset by over a 50-per-cent loss in the speaker efficiency. Increasing the compliance of the cone suspension would also lower resonance but defeat good transient response.

Other limitations, omitted for reasons of space, exist which make for mutual interdependence of speaker construction with the enclosure or other air-coupling devices employed.

B. In the Enclosure

(1) *Dimensions of Horn Mouth*

Most enclosures for home use do not comply with acoustical specifications for the horn mouth. Practical tests indicate that the mouth diameter of an exponential horn should be at least ¼ or ⅓ of a wave length at the cutoff frequency. Less than this may induce harmonic breakup. To efficiently reproduce a 50-cps note, the indicated diameter of 80 inches for a half-wave length is rarely available, even in home-built outfits. It is inadequate mouth area that is, in part, responsible for dips or maxima in bass-response curves. An attempt to avoid this deficit is illustrated in the principle of corner-wall extension of the horn mouth in the Klipsch-type horn design. This, of course, immobilizes the enclosure to the corners of a room which is not always feasible in the home.

Completely flat response of even the larger commerical enclosures down to fundamental tones of 40 or 30 cps is illusory. What one often hears, considerably attenuated, are some of the harmonies. Further, no finite exponential horn has an absolute zero output below its calculated cutoff. The rolloff incidental to the design is included in response curves to prove the merits of the particular enclosure.

(2) *Horn Rate of Flare*

Available exponential horn designs call for straight-sided walls at various

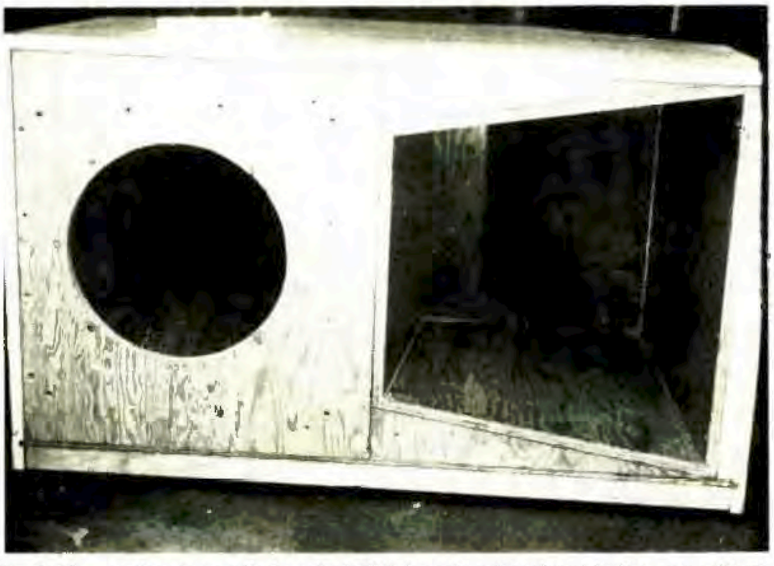

Fig. 3. The speaker is installed on its baffle board and enclosed in the raw cabinet.

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[8] W. Clements, "A new approach to loudspeaker damping," Audio Engineering, August, 1951.

[9] U. J. Childs, "Dynamic negative feedback." Audio Engineering, February, 1952.

acute axial angulations along the sound path, usually to save space. In wood-wall construction, these are not true curved-wall exponential horns, but cones. They have exponential dimensions at considerably separated junctional planes, where the air column starts a new axial direction. Such sharp reversals of the sound path, from 120 to 170 deg. in common designs, cause harmonic break-up and wasteful energy absorption by enclosure walls. Where the diameter of a plane approaches ¼ or ½ wavelength dimensions at mid-frequencies, (above 300), unavoidable phase-cancellations arise.

(3) *Path Length in Multi-way Systems*

For a straight conical horn such as a square-sectioned megaphone with a 50-cps cutoff as determined by the flare, a half-wave path length of over 10 feet is theoretically indicated. This is far too long to preserve phase relationship to a treble speaker located in a different radiation plane. As Langham[10] indicates, the short tweeter-to-ear path as compared to a long woofer-to-ear path *must* interfere with correct phasing; the resulting "divided presence" may be unpleasant. Two-, three-, or four-way systems, each with its proper horn-loading, may widely deviate from required equidistant speaker-to-ear paths. Equal path-lengths are best obtained with coaxial systems. This is achieved at a cost of lowered acoustical efficiency due to spatial limitations along the sound-path axis for two or three drivers with their mutually incompatible horn couplings.


Fig. 2. Front view—left is the speaker housing, with the horn mouth shown at the right. The two are connected by a semicircular horn.

At 30 cps cutoff, specified horn dimensions are alarming for home use (see Table II). In addition, cabinet resonance should be below that of the speaker to avoid additional spurious peaks. That well-known nemesis, the law of diminishing returns, applies with painful clarity, the lower one reaches for cutoff frequency.

The need for a large mouth and a long path length can be occasionally met in home installations. A divided exponential horn 7 feet long with a mouth 40 × 22 in. has recently been built by one purist in a four-way system to occupy an entire spacious clothes closet.[11] Another bold individual[12] built a "concrete monster" with a horn 10 or 12 feet long planted in his backyard and, having torn away a wall of his living room, had the horn mouth of 55-in. square form part of the wall. The chap who spawned this figuratively hyperbolic exaggeration (or is it really?) of low bass design, can rightly claim good bass response down to 30 cps. But how about phase agreements between, say, a 22-foot woofer-to-ear travel and a 10-foot tweeter-to-ear path of treble sound for a listener facing the system from a living room chair?

(4) *Frequency Range Restrictions*

A horn designed for the lower bass automatically limits the upper range propagation since it cannot meet the higher flare rate requirements for frequencies far above cut-off. A tuba cannot efficiently produce the treble notes of a trumpet, much less those of a clarinet or flute. The effective upper limit in a folded horn of Klipsch design is about 400 cps[13] since above these frequencies the horn diameter along its axis approaches actual dimensions or multiples of the wave lengths. The resulting reflections and defractions that arise in the tortuous and sharply angulated sound-path cause phase cancellations, spurious resonances, and varying absorption by the walls of plywood, regardless of constructional rigidity. Thus, the advantage of folding or telescoping an exponential horn to avoid awkward length is partly nullified by distortions inevitable for frequencies a number of octaves above cutoff. An approach to good reproduction of a specific segment of the audio spectrum is seen in the present 2-, 3-, and 4-way systems. Strictly speaking, proper narrow-range horn designs would call for an 8- or 10-way system to eliminate distortions, an impractical solution under present thinking.

(5) *Enclosure Construction and Unwanted Absorption*

(*Continued on page 80*)

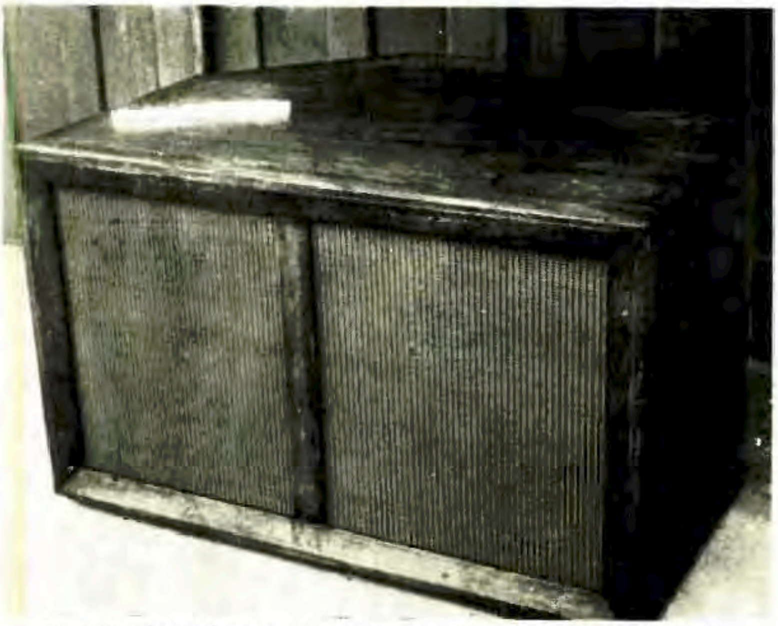
Fig. 4. The finished cabinet. On the top is seen a carpenter's rule for scale.

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[10] J. R. Langham, "*High-Fidelity Techniques*," pp. 25–28. Gernsback Publications, N. Y., 1950.

[11] E. V. Ketcham, "Evolution of the 'Horn'." AUDIO, pp. 23, December, 1954.

[12] J. Ferguson, "The Concrete Monster." AUDIO, p. 17, July, 1954.

[13] D. J. Plach and P. B. Williams, "A laboratory reference standard loudspeaker system." AUDIO ENGINEERING, p. 34, October, 1954.

SEMICIRCULAR HORN

(from page 29)

Rigidity sufficient to completely eliminate horn wall sound absorption (i.e., zero vibration and 100 per cent reflection is hard to achieve. Costs, ease of assembly, volume, and final weight dictate the use of reasonably priced and readily worked, semi-light materials, usually ¾-in. plywoods. Concrete or sand-filled walls have been recommended but are hardly attractive. Phelps[14] found attenuation of several db in wood walls partly reducible by heavy shellacing.

Definitely rigid, non-vibrating, non-absorbent material, could only consist of metal of appreciable thickness,[5] with smooth, gently curved walls as exemplified in brass instruments. Perhaps there will be adoption of the light-weight moldable fiber-glass laminates with low inherent resonance such as is used in small boat construction. This might allow construction of a more accurate continuous curved flare of true exponential form. Thick-walled, massive, one-piece plastic material, heavily braced, as used for radio consoles or auto fenders, is another possibility. At the New York 1955 audio show, massive rigidity using a 1½-in. plywood mounting baffle 4 × 8 feet across was installed for binaural demonstrations by one record maker.

The Semicircular Exponential Horn

In an attempt to have a back-loaded horn which is a reasonable facsimile of a smoothly curved, rigid-walled, musical horn, the semicircular back-loaded exponential horn was designed to eliminate or minimize some of these difficulties.

Referring to photographs, one notes a smoother air-column path in the gently curved horn than in other designs in use. There is less chance of standing waves from reflections. Since sound tends to follow an arced surface without undue loss of energy, the simulated semicircle should cause minimal horn wall absorption and inhibition of harmonies.

We are familiar with the whispering galleries or arches of churches where the soft voice is clearly carried across the width of the nave to an opposite wall. Similarly, a semicircular horn induces circumferential travel. In this design the outer arc of sound travel is an ample 8 feet within an over-all 3½ × 4 foot plane.

A true exponential flare is incompletely attained. The five component sections in the horn (see photos) are straight-sided with 45-deg. turns instead of 90 to 170 deg. conventional turns. For part of the cross-section the horn acts as a cone. Advantage of the cone flare lies in the absence of a sharp cutoff and a gradual rolloff below the equivalent cutoff of an exponential flare.

The standard exponential horn formula was used in constructing our model.

$$S_x = S_1 \varepsilon^{mx}$$

where S_x = cross-sectional area at point x
S_1 = " " " " throat
ε = 2.72 (Naperian base)
m = flare constant that determines cutoff
x = distance from throat to S_x or cross-sectional area

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[4] W. D. Phelps, "Vibration and absorption of sound in horn walls." *J. Acous. Soc. Am.*, 12: 68, 1940.

[5] Sound energy of 20-40 watts passing through a French Horn, as usually blown, would induce tremendous vibration of its thin brass wall.

The horn has a 32-cps cutoff, below the speaker cone resonance of 35. A tapered "mouthpiece"[16] (or speaker chamber) leads into a roughly square throat of 100 square inches to minimize harmonic breakup of low fundamental tones (see Table II). With a constant exponential flare and mouth, increasing the throat area will help smooth out bass response by separation of successive maxima obtained in bass response curves. The cross-sectional area of this horn doubles every 24 inches and has flare rate of .028.

The mouth area had to conform to a reasonable (for me) size and this was determined as 22 inches square (480 s.i.) in the plane of the speaker baffle mount. If truly exponential, this mouth represents a cutoff at 125 cps, but since the horn has some acoustic qualities of a cone, rolloff to 30 to 40 cps is present.

The axial sound path is 5½ feet long and corresponds to a half wavelength at 100 cps. Consideration is due to the 8-foot path length along the outer arch which should permit propagation at frequencies of 60 cps and lower.

Some experimental geometry was needed in "bending" this horn in a semicircle to prevent inside-curve compression of the air column. The square cross-section for the throat had to be modified in favor of a trapezoidal pattern. Only in this fashion could a final mouth outline avoid a triangular pattern which would restrict the mouth circumference.

For the horn walls, over 60 square feet of plywood was used. It was constructed of ¾-in. 5-ply, heavily braced at joints, splined, and glued. All interior joints were spackled to smooth out the curves. The interior received three generous coats of shellac to further decrease sound absorption in the gently curved horn path. The speaker baffle board was air-sealed with caulking compound to the speaker chamber. It will be seen that the finished cabinet envelope (see Fig. 3) enclosed an air space between its walls and the enclosed horn. It was decided not to fill this dead space since no additional absorption was necessary to deaden the horn walls.

A corresponding alteration of the junction between speaker chamber and throat was made. It will be noted that beginning with the baffle mount, there is gradual taper up to the throat to avoid breakup of tones below 50 cps.

From another viewpoint, the five conjoined truncated sections simulate a manifold exponential horn. For example, the throat area of one section matches the mouth plane of the preceding section. Such a manifold horn will accept a wider frequency range.

The finished horn is a compromise as are most others in use. It deviates from the ideal smoothly-flared circular exponential horn as follows:

1. It is roughly square in cross-section (trapezoidal in many planes) instead of circular.
2. It is conical in each of five major sections, short-cutting the minimal increments that would effect a smoother exponential curve.
3. It is a series of roughly square pyramidal sections.
4. It is a finite horn angulated at 45 deg.
5. It approximates specifications for a 125 cps cutoff.

To feed one's vanity these compromises could be vigorously defended as less drastic deviations from true horn dimensions than most existing designs—corner type, folded design, and so on.

In actual practice the theoretical considerations are amply substantiated. With an audio signal generator our semicircular exponential horn has beautiful bass response down to 40 cps. Below this, distinct wave pressure causing palpable pants-leg flutters, was experienced. The rumble in this bottom range, with a good changer and pickup combination, is distinctly perceptible.

The audio components terminating in the back-loaded horn consist of the highly sensitive Craftsmen C-1000 with phono, television and professional tape deck feeding a Fisher 30-watt amplifier, with a damping factor of 29 and a Stephens 15-in. coaxial 206AXA speaker with further damping from a 7½-lb. magnet. This bass-restricting effect was offset by the large air-mass loading of the woofer. Originally housed in a bass reflex cabinet of recommended dimensions, the speaker's bass response had been discouragingly weak. After installation in the new enclosure, with back loading of the woofer, we noted:

1. Flat to slightly enhanced bass response audibly smooth down to 40 cps (in spite of combined amplifier-speaker magnet damping).

2. Undistorted reproduction of tympani, bass viol, tuba and trombone tones. Turntable rumble was clearly audible though not exaggerated.

3. Some attenuation around 300 cps, possibly from phase cancellation.

4. Mild reinforcement at frequencies from 500 to woofer crossover at 1200.

5. Non-directional radiation up to 200 cps, from the horn mouth—22 in. square.

Repeated compliments by critical listeners, musicians, engineers, and rabid hi-fi enthusiasts on the clean, low tones, have happily confirmed the value of this type of back-loaded low-frequency horn. In floor space requirements and coaxial propagation of the audible range it satisfied conventional standards. All sounds come from the front speaker plane with no divided-presence effect.

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[16] The lower range brass instruments use tapered mouthpieces while trumpets use a cup mouthpiece to induce propagation of harmonics.