A Revised Low-Frequency Horn of Small Dimensions*

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More than 50 years after the introduction of the KLIPSCHORN, a revised low-frequency horn for the system is presented, which will return the system to a two-way design as originally envisioned by its inventor. How this was achieved is discussed with the support of data and results.

0 INTRODUCTION

Paul Klipsch's paper describing a low-frequency horn was first published in 1941 [1] and subsequently reprinted in this *Journal* in 1979 [2]. The paper described the thoughts and reasoning behind the KLIPSCHORN[1] low-frequency horn. Today, more than 50 years after its introduction, the low-frequency section of the system remains for the most part unchanged. The current loudspeaker is a three-way, fully horn-loaded system, which still commands respect in the company of most of today's high-end loudspeakers.

1 BACKGROUND

Although the first production units of the KLIPSCHORN were a two-way design, it was soon changed into a three-way system to improve the high-frequency performance. As far back as 1986, Klipsch had wanted to return the system to its original two-way design. His contention was that by getting the KLIPSCHORN's low-frequency unit up to about 600 Hz, one of the large compression drivers could be used to do the rest. He had envisioned laying out the low-frequency unit in such a way that all the bending of the horn could be done in one plane. The low-frequency section of the current system is bent in two planes and is a rather complex geometric cabinet. This complicated bending limited the high-frequency response of the low-frequency horn to 500 Hz. Fig. 1 gives a cutaway of the current horn.

The advantages of horns are well known. Many designs have been implemented and some patented [3], [4]. The efficiency and the low distortion characteristics of properly engineered horn-loaded cabinets are not rivaled by vented or sealed systems. Horn-loaded low-frequency sections must be large to go down to any appreciable cutoff frequency. And small horn-loaded low-frequency sections have a high cutoff frequency, typically in the 60–100-Hz range. One major advantage of the current low-frequency unit is that it has a cutoff of 38 Hz and is still able to fit into most living rooms. It takes advantage of the fact that it operates in a corner (one-eighth space). Therefore it does not require the large mouth the same horn would need if it were to operate in full space. Because the driver is horn loaded, the amount of excursion it undergoes is reduced, and thus distortion is also reduced. A driver that is able to withstand 250 W of input power produces high sound

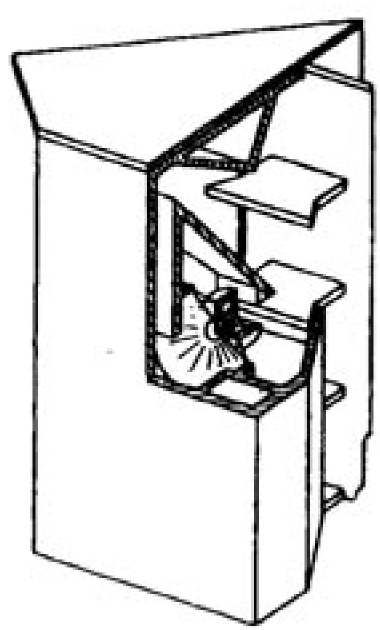

Fig. 1. Cross-sectional view of current horn.

* Manuscript received 1998 September 15; revised 2000 March 29.

[1] Registered trademark of Klipsch and Associates, Inc.

pressure levels (SPLs) because of the efficient loading of the horn. The new low-frequency unit is to have all of this as well as the ability to go 200 Hz higher (1/2 octave) than the current low-frequency unit.

2 GLOSSARY OF SYMBOLS

B = magnetic flux density in driver air gap
c = velocity of sound in air, = 343 m/s
C_{ms} = mechanical compliance of driver suspension
f_c = horn cutoff frequency
f_s = resonance frequency of driver in free air
l = length of wire in air gap
L_e = inductance of driver voice coil
m = flare constant
M_{ms} = mechanical mass of driver diaphragm assembly, including air load
P_e = nominal electric input power
Q_{es} = Q of driver at f_s, referenced to R_E
Q_{ms} = Q of driver mechanical system at f_s
Q_{ts} = total Q of driver at f_s
R_E = dc resistance of driver voice coil
S = cross-sectional area
S_d = effective surface area of driver diaphragm
S_T = throat area
V_{as} = volume of air having same acoustic compliance as driver suspension
V_B = volume of air in back air chamber
x = length of horn at a given point.

3 LAYOUT OF HORN

3.1 Trying to Maintain One Flare Rate

Fig. 2 illustrates the low-frequency horn across its horizontal plane. The area expansion is analyzed at three points along the horn expansion. These three points represent the three straightest parts of the horn, essentially three linear expansion sections. The area expansion of the horn was to follow the exponential equation as closely as possible and to maintain a consistent flare rate from section to section.

3.1.1 Area Analysis at Point B

The throat area in point A is 0.029 m^2. The length of the horn from point A to point B is 0.209 m. Using the following equations from Beranek [5], we find what the area at point B should be,

$$S = S_T e^{mx} .$$

The variable m must first be determined as follows:

$$m = \frac{4\pi f_c}{c} = \frac{4\pi(38)}{343} = 1.392 m^{-1} .$$

The calculated area at point B is determined using the following equation:

$$S = 0.029 e^{(0.1392 \times 0.209)} = 0.038 \text{ m}^2 .$$

The actual area at point B is 0.061 m^2. The actual cutoff frequency for this section is found as follows:

$$S = S_t e^{mx}$$

$$0.061 = 0.029 e^{m(0.209)}$$

$$m = 3.635 m^{-1} .$$

Then

$$f_c = \frac{mc}{4\pi} = \frac{(3.635)(343)}{4\pi} = 97 \text{ Hz} .$$

3.1.2 Area Analysis at Points C and D

Similarly, using the equations presented we can find the areas at points C and D. Looking at Fig. 2, Table 1 summarizes the expansion of the horn at the four points.

3.2 Dual Drivers

Fig. 2 illustrates the horn in cross section, showing only one driver being loaded in the cabinet. Because the horn is bent in only one plane, the height of this horn

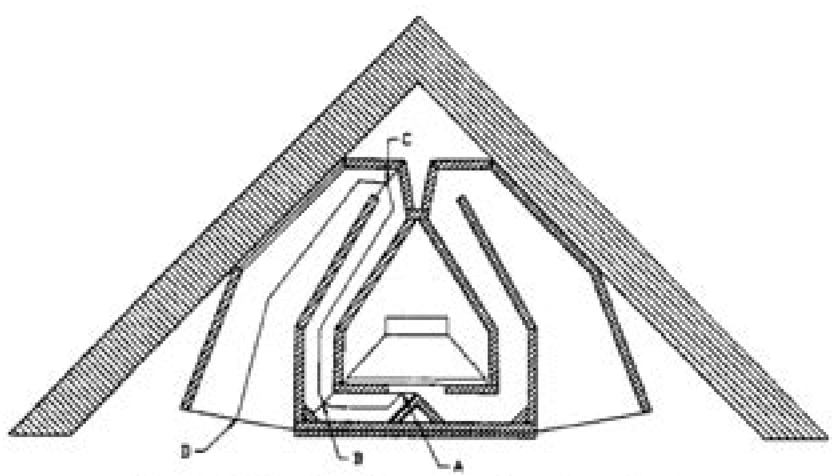

Fig. 2. Points along horn expansion to be analyzed.

would only need to be 0.482 m. However, the overall height requirement dictated that the low-frequency section be 0.964 m tall in order to provide optimum height placement for the high-frequency section. Therefore the low-frequency section is configured with dual 0.305-m (12-in) drivers.

These drivers are appropriate for horn loading. Using Keele's equations [6] to determine appropriate drivers for horn loading, one finds the Thiele/Small [7] electromechanical and mechanical parameters as follows:

f_s = 19 Hz
Q_{es} = 0.193
Q_{ms} = 4.410
Q_{ts} = 0.185
V_{as} = 386 l = 0.386 m^3
C_{ms} = 9.69×10^{-4} m/N
M_{ms} = 71 g
Bl = 15.9 T · m
R_E = 5.7 Ω
S_d = 0.053 m^2
L_e = 1.338 mH
P_e = 250 W.

3.2.1 Midband Efficiency

The throat area needed to maximize the midband efficiency is given by

$$S_T = \frac{2\pi f_s Q_{ts} V_{as}}{c} = \frac{2\pi(19)(0.185)(0.386)}{343} = 0.025\ \mathrm{m}^2 .$$

The actual throat area is 0.029 m^2.

3.2.2 Back Air Volume Requirements

The back air volume can be calculated by the following equation:

$$V_B = \frac{V_{as}}{f_c/f_s Q_{ts} - 1} = \frac{386}{[38/(19)(0.185)] - 1} = 39.3\ l .$$

The actual back air volume is 37 l per driver.

3.2.3 Reactance Annulling Check

To check for proper reactance annulling, the following equation checks to see how close it is to the cutoff frequency f_c:

$$f_c = Q_{ts} f_s \left(1 + \frac{V_{as}}{V_B}\right) = (0.185)(19)\left(1 + \frac{386}{37}\right) = 40\ \mathrm{Hz} .$$

As a further check, Fig. 3 displays the impedance plot of the system.

3.3 Splaying the Horns

The original KLIPSCHORN low-frequency section uses three mutually perpendicular surfaces to extend the length of the horn. The subject prototype was to follow suit. Fig. 4 illustrates the original layout of this horn. The frequency response of this layout, illustrated in Fig. 5, shows the high-end response of the system rolling off rapidly above 500 Hz. Since one of the original objectives was to have the low-frequency section cross over around 600–700 Hz, the geometry of the horn had to change to ensure adequate acoustic output in this region. Fig. 6 shows that the low-frequency section basically consists of two horns with their mouth centers separated by a distance of 0.699 m and splayed at a 72° angle. If the angle and the distance between the two horns are decreased, then the output at the on-axis point A between the horns begins to increase. Since moving in the horns, and thus decreasing the angle between them, caused the wall of the second section (B in Fig. 6) to move, there was a finite distance that the walls could be moved inward before affecting the area expansion of the second

Table 1. Flare rate analysis.

Location	Length (m)	Area of Horn (m^2)	Area per Equation	Flare Rate
Point A	0	0.029	0.029	0
Point B	0.209	0.061	0.038	97
Point C	0.741	0.075	0.081	35
Point D	1.402	0.232	0.204	40

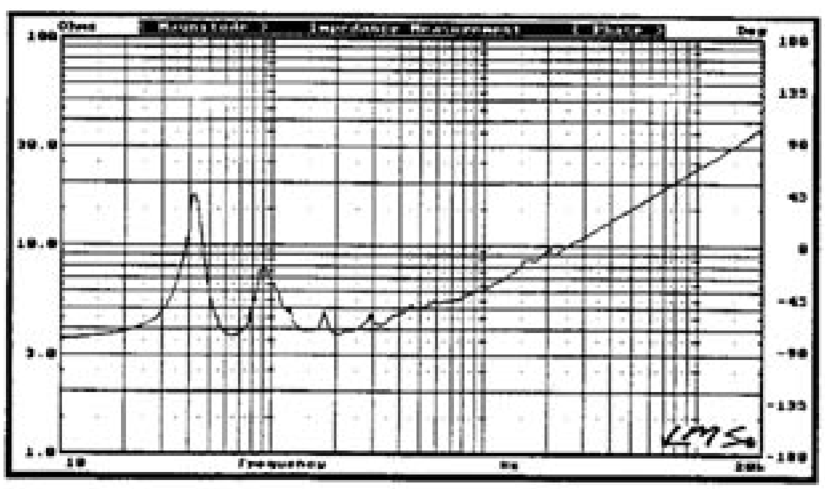

Fig. 3. Impedance response of new horn.

section. If one then moves the wall of the second section, which also corresponds to the wall of the back air chamber (C in Fig. 6), then the whole layout of the horn is affected. The maximum convergence angle that the horns could be brought in for a sound pressure increase in the on-axis position A and the minimum space needed to ensure that a horn could be laid out had to be determined. Fig. 7 illustrates the results. Due to this bend in the last 0.33 m of the horn, the horn is required to have a "built-in" corner, ensuring that the top end of the frequency response is maintained and enabling a proper crossover to the high-frequency section. The design still recognizes the fact that it will be loaded in one-eight space but does not absolutely require that a corner be available for proper operation.

4 ANALYZING THE DATA

The flare rates at points B, C, and D are 97, 35, and 40 Hz, respectively. The first section of the horn, at point B, has a high flare rate when compared to the other sections. In order to change the flare rate to closely match the desired cutoff of the horn of 38 Hz, we would need to decrease the height of the cabinet and perform some other modifications to the housing, which could turn into some rather complicated compromises. A higher flare rate at the throat of the horn is not without precedent. As described in Klipsch [1], a "rubber" throat is a throat geometry that provides a high flare rate at the initial start of the horn. With the current throat opening and at low frequencies, this would develop an unusually high load. This high flare rate section would increase the apparent throat opening. With this and other factors in mind, to modify the cabinet in order to match the flare rate of the other sections would cause other aspects of the cabinet design to change. This would compromise the performance of the horn.

The calculated throat area needed to maximize the midband efficiency is 0.025 m^2. The actual throat area is 0.029 m^2. This results in an error of 13%. Again, the throat area could have been increased, but was not because of the reasons stated.

The calculated volume of the back air chamber is 39.3 l, the actual volume is 37 l. The back air chamber could have been increased by increasing the height of the cabinet. Increasing the height of the cabinet could have also lowered the reactance annulling frequency. It was calculated to be at 40 Hz, but should be at 38 Hz. From Fig. 8, the response did not justify increasing the height of the cabinet.

The most significant improvement to the low-frequency section came when the splay angle and the distance between the horns were changed. Looking at Fig. 6, the original distance and splay angle between

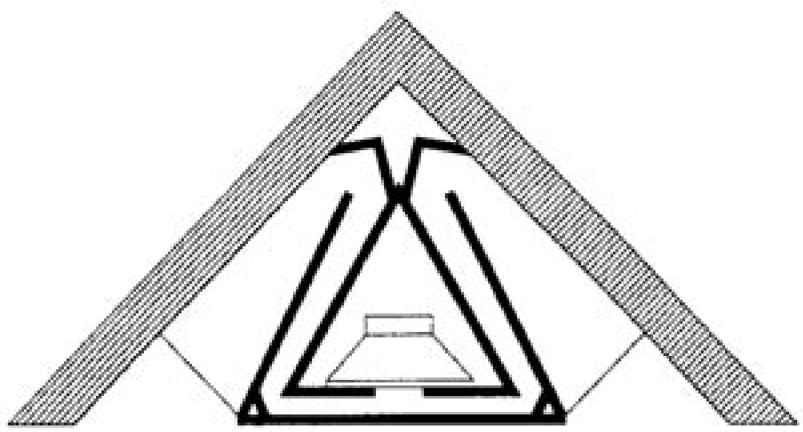

Fig. 4. Cross-sectional view of original prototype.

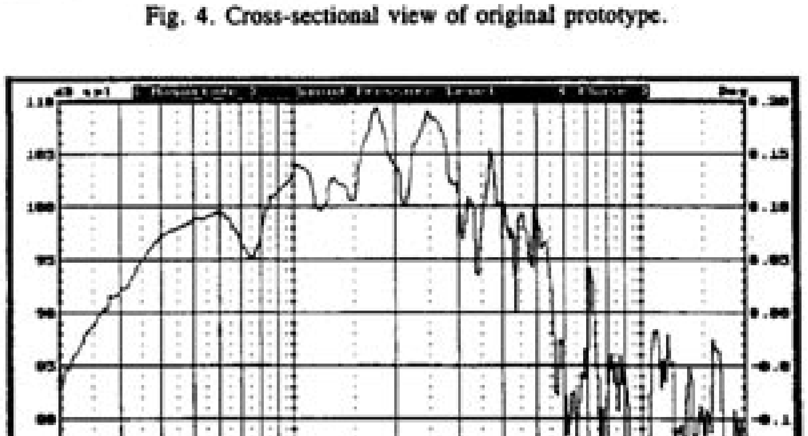

Fig. 5. Frequency response of original prototype.

the two horns were 0.699 m and 72°. The frequency response of this layout, illustrated in Fig. 5, indicates that the top end of the horn is rolling off rapidly above 500 Hz. The distance and splay angle were changed to the minimum values allowed by the design. An additional constraint was the use of 0.305-m drivers. Decreasing the distance and splay angle further would have necessitated that 0.254-m drivers be used. Fig. 7 illus-

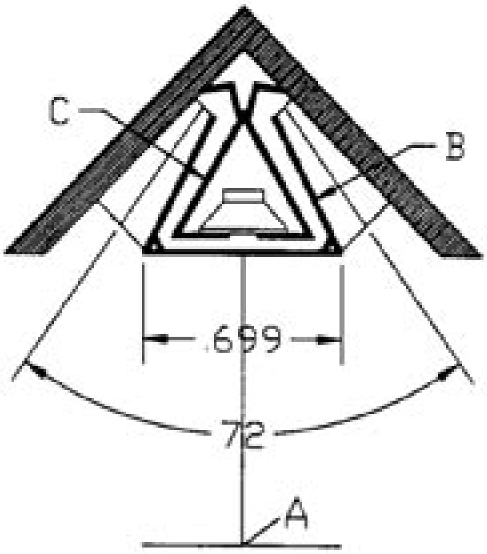

Fig. 6. Original angular separation and distance between two horns.

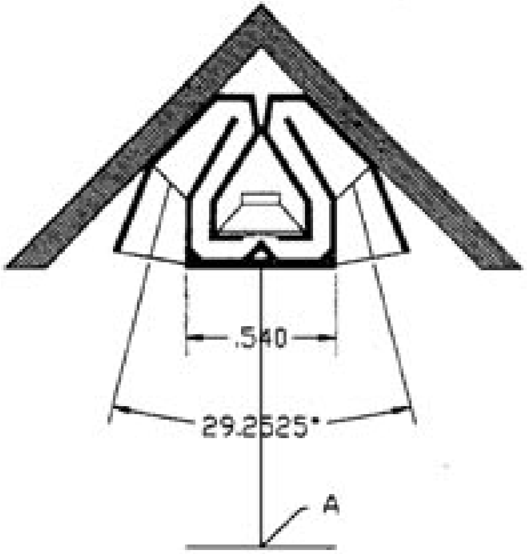

Fig. 7. Final angular dimension and separation distance between two horns.

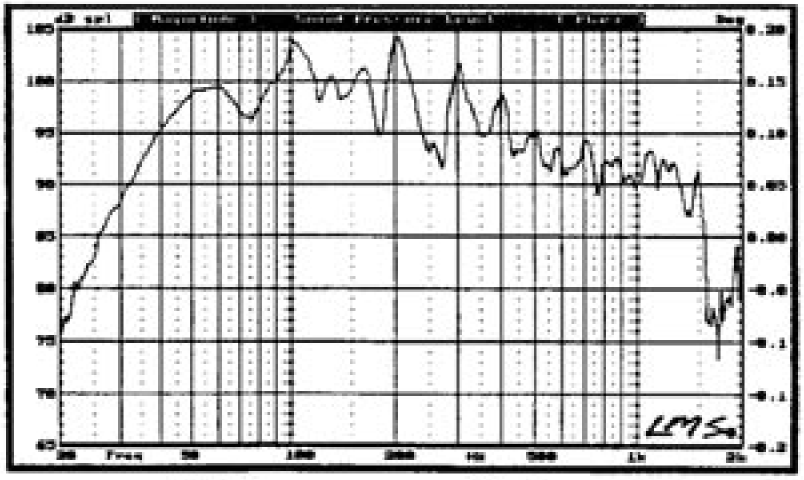

Fig. 8. Frequency response of final prototype.

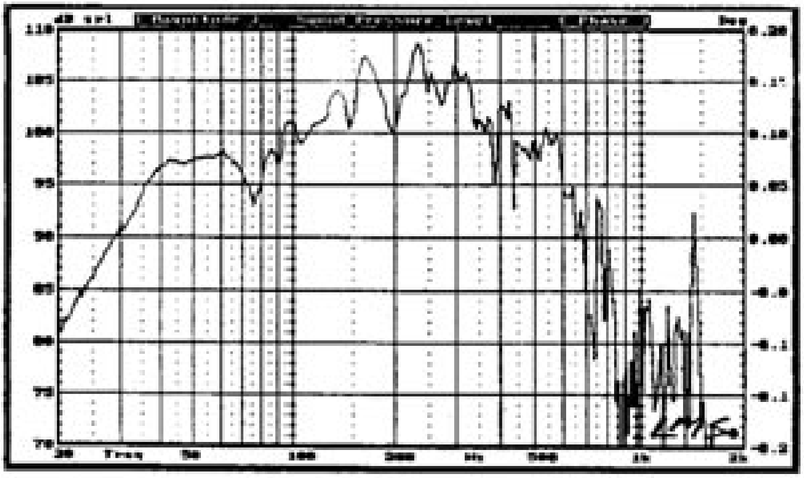

Fig. 9. Frequency response of current horn.

trates the final layout.

When folding a horn in this manner, changing one dimension or angle in order to match calculated values has many ramifications. Considering all the possible variables that must match, the final layout offers the solution that contains the fewest compromises and provides the most benefits.

5 COMPARISON WITH OLD HORN

5.1 Frequency Response

Figs. 8 and 9 show the frequency responses of the new low-frequency section and the current low-frequency section, respectively. Both curves were generated in one-eighth space, outdoors, microphone centered on the cabinet axis, and at a distance of 2 m. In the area between 50 and 120 Hz the new low-frequency section shows an improvement that is very noticeable in music playback. The output of the dual 0.305-m drivers in the new low-frequency section compared to the output of the single 0.381-m driver in the old design shows a smoother response in the passband. The upper frequency limit of the old low-frequency section is approximately 550 Hz, whereas the upper frequency limit of the new design is approximately 1500 Hz. The new horn does show a slight decrease in the flare rate in the 35–40-Hz region when compared to the current horn.

5.2 Mouth Area and Length of Horn

The effective mouth area of the new low-frequency section is 0.232 m^2 for each driver, or 0.464 m^2 in total. The effective mouth area of the old low-frequency section is 0.372 m^2. The mouth area for a 38-Hz horn designed to operate in free space using the exponential equation is 6.516 m^2, with a total horn length of 3.378 m. The mouth area required to operate in one-eighth space is 0.814 m^2 Apparently the mouth area that is available is sufficient to load the drivers down to 40 H. From Fig. 8, the −3-dB down point is approximately 40 Hz. The fact that the horn will be operated in rooms helps overcome the shortage in mouth area. In true one-eighth space loading, the output in the 35–40-Hz region will decrease.

5.3 Distortion Data

As a further test of the improvement of the new horn, second and third harmonic distortion tests were conducted at an input voltage of 13 V. Figs. 10 and 11 show

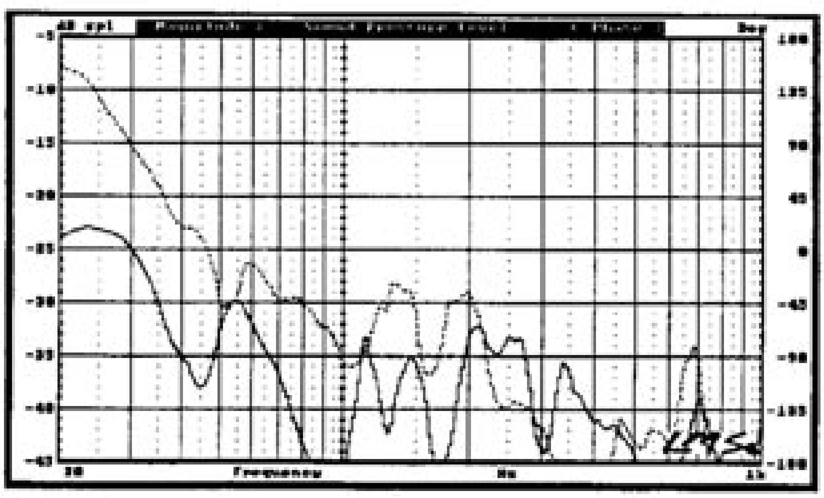

Fig. 10. Second harmonic distortion. —— final prototype; – – – current horn.

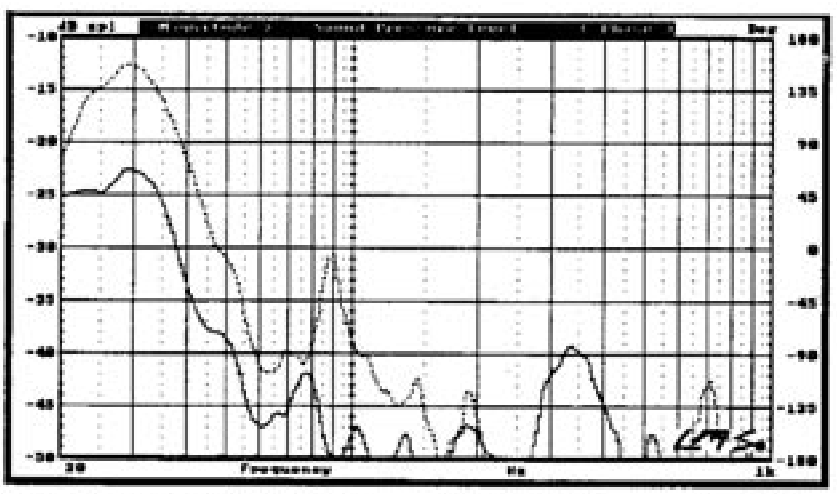

Fig. 11. Third harmonic distortion. —— final prototype; – – – current horn.

the data, comparing the new horn with the current horn. The curves are normalized to the fundamental. By looking at the curves, second and third harmonic distortion is reduced. Both curves shown an improvement over the original horn, although there is a slight increase between 250 and 400 Hz.

6 CONCLUSION

Our first goal was to match the performance of the current low-frequency section. Improving the current KLIPSCHORN low-frequency unit presents a formidable task. After all, this loudspeaker was the basis and anchor of the company that Paul Klipsch started.

The frequency responses of the current low-frequency cabinet and the new low-frequency cabinet, shown in Figs. 9 and 8, show at the very least that the new design matches the performance of the current low-frequency cabinet. The design does provide some significant improvements.

1) Smoother response in the passband
2) Decrease in second and third harmonic distortion
3) Very noticeable improvement in the dip between 50 and 120 Hz
4) New low-frequency cabinet having the same footprint as the current one
5) Increase in upper frequency limit, Klipsch's main goal
6) Folding the horn in one plane to provide a more consistent, defined area expansion for a 38-Hz horn.

7 ACKNOWLEDGMENT

The authors wish to thank the following members of the Klipsch engineering staff: Mike Faulkner for all the excellent prototypes executed flawlessly; Kerry Geist and Dan Field for proofreading the manuscript and for their advice; and the rest of the staff. Thanks for patience, advice, and support. Roy Delgado wishes to personally thank Paul W. Klipsch for giving him the opportunity to work on his life's work, the KLIPSCHORN.

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THE AUTHORS

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Roy Delgado Jr. was born in Donna, TX, in 1962. He received a B.S.E.E. from the University of Texas at Austin in 1985. After graduating he went to work for Klipsch and Associates from 1986 to 1995 as a design engineer for the professional and consumer products divisions. As part of a design team, the company's first sound reinforcement model was introduced that featured a fiberglass shell. A patent was awarded to the design team for the uniqueness of the product. From late 1993 to 1995, he was promoted to chief engineer. From 1995 to 1998, he worked for WWR, d.b.a. Klipsch Professional, as a design engineer and was later promoted to chief engineer. It was during this time that he started a consulting company, working on projects outside the professional market, and was awarded a patent involving horn loading a vented cabinet. He is currently working for Klipsch LLC as chief engineer for the professional products division. He is a member of the Audio Engineering Society.

Mr. Delgado's interests include a stronger relationship with God, the pursuit of the ever-elusive largemouth bass, and continual tinkering with the acoustic horn.

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Paul W. Klipsch was born in 1904 in Elkhart, Indiana. He received a B.S. degree in electrical engineering from the New Mexico College for Agricultural and Mechanical Arts in 1926 (now New Mexico State University), an engineering degree from Stanford University in 1934, and a Doctor of Laws (hons, caus.) from New Mexico

State University in 1981. He worked for the General Electric Company, Anglo Chilean Nitrate Corp., in Tocopilla, Chile; in geophysical prospecting in Houston, Texas; and in the U.S. Ordnance Dept. (Major–1934, Lt. Col.–1953). He started Klipsch and Associates, a manufacturer of loudspeakers, and sold the company in 1990. He is listed as Founder and Technical Adviser of Klipsch LLC.

Mr. Klipsch has written papers and holds patents in the fields of geophysics, acoustics, and firearms. He is a fellow of the Audio Engineering Society, of the IEEE, and of the Acoustical Society of America. He is a member of Tau Beta Pi and Sigma Xi and is listed in *Who's Who in Engineering*. He is a recipient of the Audio Engineering Society Silver Medal (1978) for his contribution to loudspeaker design and for measurement of distortion. He was inducted into the Audio Hall of Fame in 1983 and the Engineering and Science Hall of Fame in 1997. New Mexico State University renamed their Engineering and Computer Engineering Department to the Paul W. Klipsch Department of Electrical and Computer Engineering (1994).