TOTAL DISTORTION IN MODERN THEATRE WOOFER SYSTEMS

FROM THE BOXOFFICE MAGAZINE SERIES

By
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First, I would like to thank James R. Hunter, Kerry Geist and Roy Delgado of Klipsch and Associates, Inc. for their help in preparing this article.

Loudspeaker introduced distortion is an old yet often misunderstood subject. Speaker systems are well known producers of several kinds of distortion; some benign, some not. Historically, some quarters, particularly at the marketing level, have chosen to ignore or confuse the issue, while others actually deny what one manufacturing executive called the "black secret" of loudspeakers.

Outright deceptions can be found. One article claimed that "horn" type theatre woofers produce greater distortion than do direct radiator types. Yet the woofer actually tested for the article was not a fully horn loaded woofer. Rather, the system tested was a large vented box / direct radiator system which incorporated a short (less than 3 foot) upper bass horn section.

Confusing or not, most discussions about speaker distortion have, unfortunately, concentrated only on harmonic non-linearities, completely failing to mention other greater, and arguably more offensive, forms of quality killing distortion.

This article describes the research and findings of a rather exhaustive series of tests. The tests were designed to measure both the harmonic distortion and the modulation (sometimes called intermodulation) distortion levels generated by a modern fully horn loaded woofer and a direct radiator type. Distortion is considered to be ANY frequencies found in the speaker's output which were not present in the input signal.

Driver performance plays an important factor in such an investigation. To eliminate any discrepancies which might be traced to different drivers, these tests were conducted with the SAME two 15 inch drivers mounted in each enclosure under test. The importance of this test condition cannot be stressed enough, yet it is very rarely done.

Results were obtained for both systems at several frequencies and near-field output levels up to 140 dB Sound Pressure Level (SPL). In both systems, the often cited harmonic

distortion was found to be substantially equivalent; though the direct radiator did less well at the highest levels measured. The modulation distortion components were found to be as much as ten times greater in the direct radiator as compared to the real horn.

BACKGROUND

It's been over 40 years since Beers and Belar published their often cited paper on modulation distortion in loudspeakers and its deleterious effects [1]. Since then, the more sales oriented discussions of loudspeakers have tended to ignore or hide distortion.

Unlike the makers of power amplifiers, the majority of speaker manufacturers generally do not include harmonic or modulation distortion data in their product literature. Of those that do, it is extremely rare for modulation distortion to be mentioned. This is peculiar in as much as of the two types of distortion, modulation distortion is almost always the greater in magnitude [2]. Many consider this type of distortion by far the more offensive because, unlike harmonic distortion, its components are not harmonically related to the fundamental frequencies. Kurtin found that notwithstanding plausible arguments to the contrary, "the amount of modulation distortion typically present in high-fidelity loudspeaker systems is a real, significant and easily audible problem" [3].

With the advent of wide releases of motion pictures containing wide dynamic range recordings and particularly with digital soundtracks becoming available, motion picture theatre sound systems are required to deliver correspondingly greater output levels. Two types of low frequency theatre loudspeakers have come into general use: the fully horn loaded type and the direct radiator.

Neither of these types should be confused with theatre speakers of the past which combined elements of both horn loading and vented box constructions. Though misleading, these systems are often referred to as "horns." However, these combination systems are not fully horn loaded. It should also be noted that modern fully horn loaded woofers produce roughly ten times the output at the lowest frequencies, yet are about one half the size and weight of the older combination systems.

For the purposes of this paper, the term "HORN" refers only to a fully horn loaded device. The term "direct radiator" or "VENT" refers to such units in which horn loading is absent. Distortion refers to frequencies generated by the device under test which are not part of the original signal(s). Modulation distortion consists of both amplitude and frequency modulation distortion products.

Properly applied, HORN loading provides greater acoustic output and, in our experience,

demonstrably cleaner sound. Moir stated that the horn's "characteristic clarity is largely due to the absence of Doppler (modulation) distortion" [4]. The horn's greater efficiency allows the driver's excursion for any given output level to be significantly reduced. Reducing a diaphragm's motion also reduces those distortion products related to its displacement: namely, modulation distortion. Direct radiator type systems are generally smaller than HORN systems of similar frequency range and are popular, if not mandatory, where cabinet size or portability is an issue.

Since both types of enclosures have evolved over the past two decades, it was felt that up to date distortion comparisons should be done. Each of the woofer types tested is currently operating in contemporary motion picture theatre sound Systems.

Figure 1.

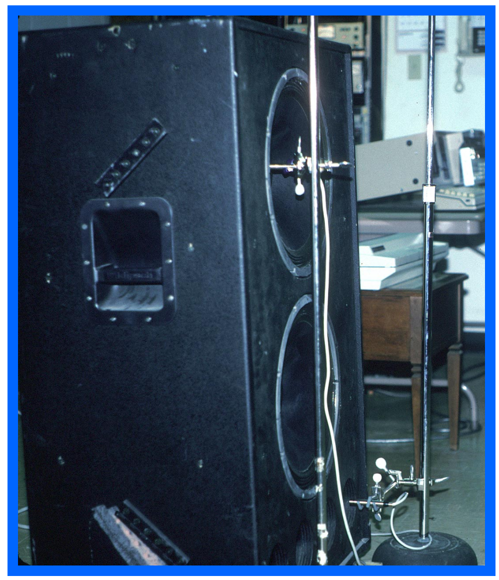


Figure 2.

SET-UP

The two woofer cabinets tested consisted of a dual 15 inch fully horn loaded enclosure (HORN) with a sealed back air chamber and a designed lower cutoff of 45 Hz, (Fig. 1), plus a dual 15 inch vented enclosure (VENT) with a designed lower cutoff of 40 Hz. (Fig. 2).

In an attempt to obtain the most accurate results, Keele's near-field measurement technique was used for harmonic tests [5]. This technique has several advantages in that it offers better signal-to-noise ratios, eliminates room nodes from the measurement and provides more accuracy at low frequencies. This approach measures the acoustic intensity near the diaphragm, or HORN mouth, and thus is not altered by the coverage angle (Q). This measuring technique is actually a disadvantage for the HORN because the effect of the coverage angle is eliminated. (Figures 1 & 2).

MEASUREMENT EQUIPMENT INCLUDED:

2 B&K 1/2 inch microphones, type 4133
1 B&K dual channel power supply type 2607
2 Hewlett Packard 3325A function generators
1 Urei microphone preamplifier
1 Teac mixer model 2A
1 Tecron TEF system 12 plus
1 Crest 8000 power amplifier
1 Hewlett Packard 3400A RMS voltmeter

The tables and graphs contain the following:

- **Harmonic distortion data with fundamentals at 40, 50, 60 and 70 Hz.**

- **Modulation distortion data with f1 and f2 at 50 and 230 Hz.**

INTERPRETATION OF THE DATA

HARMONIC DISTORTION

As the woofer is swept in frequency, the cone excursion is inversely proportional to frequency. In other words, at a low frequency, a driver will undergo relatively large excursions compared to its motion at a higher frequency. These excursions are, of course, directly related to the sound pressure level (SPL) output of the driver. When a driver reaches its excursion limits, it reaches its non-linear region. When operating below the designed low frequency cutoff, the back air chamber of the HORN also introduces non-linearities.

Each of the numbers in the following tables represent the levels of the 2nd through the 6th harmonic distortion products. The levels are expressed in the number of decibels below the level of the fundamental frequency. In other words, the greater the negative number, the better. Though input voltages as high as 41 volts are used, the typical peak voltages encountered in a 100 foot long theatre would be around 28 to 44 volts for a direct radiator (depending on its sensitivity) and only about 16volts for the HORN.

HARMONIC DISTORTION AT 40 Hz

		2ND	3RD	4Th	5Th	6TH
120 dB						
VENT	2.6V	-36 dB	-47	<-50	-48	<-50
HORN	2.9V	-40	-47	<-60	-54	-59
125 dB						
VENT	4. 8V	-31	-50	<-55	-46	-53
HORN	5.3V	-34	-38	<-55	-54	<-55
130 dB						
VENT	9. 2V	-27	-49	<-55	-45	-55
HORN	9 .4V	-29	-28	-53	-54	-58
135 dB						
VENT	19.5V	-22	-27	<-45	-44	<-55
HORN	17.5V	-22	-18	-40	<-55	-54
140 dB						
VENT	41.0V	-16	-18	-40	-43	<-45
HORN	38.0V	-12	-8	-23	-38	-40

Table 1.

Table 1: The data for 40 Hz reveals that the harmonic distortion levels are essentially equal for both the HORN and the VENT, even though the HORN is operating below it's designed lower cutoff. As expected, the non-linearities of the HORN's back air chamber become more evident at the highest output levels. With both cabinets, the drivers are in their non-linear range at the upper voltages.

HARMONIC DISTORTION AT 50 Hz

		2ND	3RD	4Th	5Th	6TH
				120 dB		
VENT	1.9V	<-50 dB	<-50	<-50	<-50	<-50
HORN	1. lV	-48	-55	<-55	<-55	<-55
				125 dB		
VENT	3.5V	-45	-50	-55	<-55	<-55
HORN	1.8V	-52	<-55	<-55	<-55	<-55
				130 dB		
VENT	6.2V	-38	-48	<-55	-51	<-55
HORN	3.2V	<-50	<-50	<-50	<-50	<-50
				135dB		
VENT	12.0V	-33	-44	-49	-50	-55
HORN	5.6V	-50	<-55	<-55	<-55	<-55
				140 dB		
VENT	23.5V	-25	-32	<-50	-46	<-50
HORN	l0.0V	-45	<-55	<-55	<-55	<-55

Table 2.

HARMONIC DISTORTION AT 60 Hz

				120 dB		
	2ND	3RD	4Th	5Th	6TH	
VENT	1.8V	-48 dB	-55	<-55	<-55	<-55
HORN	1.5V	-50	-55	<-55	<-55	<-55
				125 dB		
VENT	3.4V	-49	-44	<-55	<-55	<-55
HORN	2.6V	-51	-54	<-55	<-55	<-55
				130 dB		
VENT	5.8V	-46	-44	<-55	-52	<-55
HORN	4.7V	-52	-53	<-55	<-55	<-55
				135 dB		
VENT	10.5V	-39	-37	<-55	-54	<-55
HORN	8.5V	-49	-52	<~55	<-55	<-55
				140 dB		
VENT	19.5V	-33	-31	-52	-51	<-55
HORN	16.0V	-52	-46	<-55	<-55	<-55

Table 3.

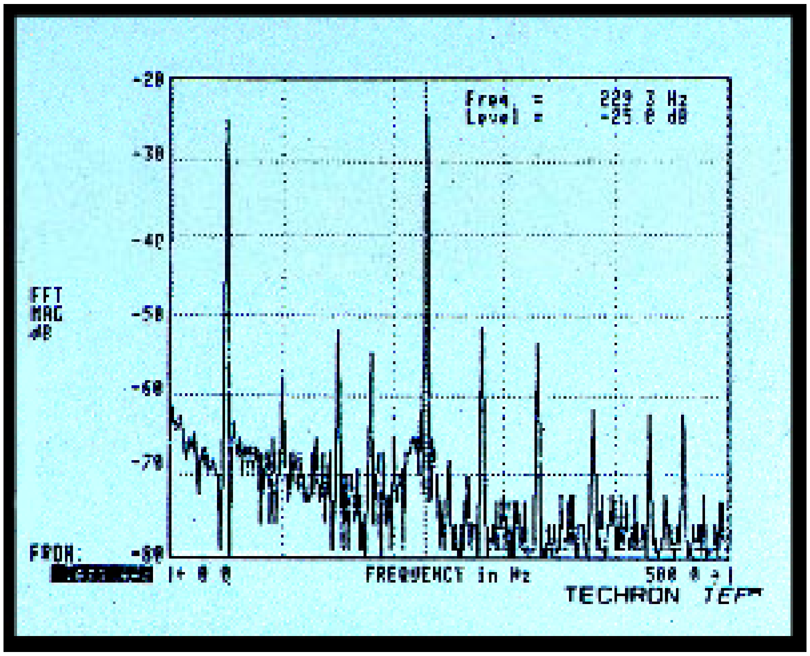
Tables 2 and 3: At 50 Hz and 60 Hz, the harmonic components of the VENT are sometimes large when compared to the HORN. At these frequencies, we are well into the designed operating range of both systems. But the HORN is more efficient, requiring less voltage than the VENT to obtain the same SPL. Therefore, the HORN is not nearing a non-linear region as is the VENT at the higher voltages.

HARMONIC DISTORTION AT 70 Hz

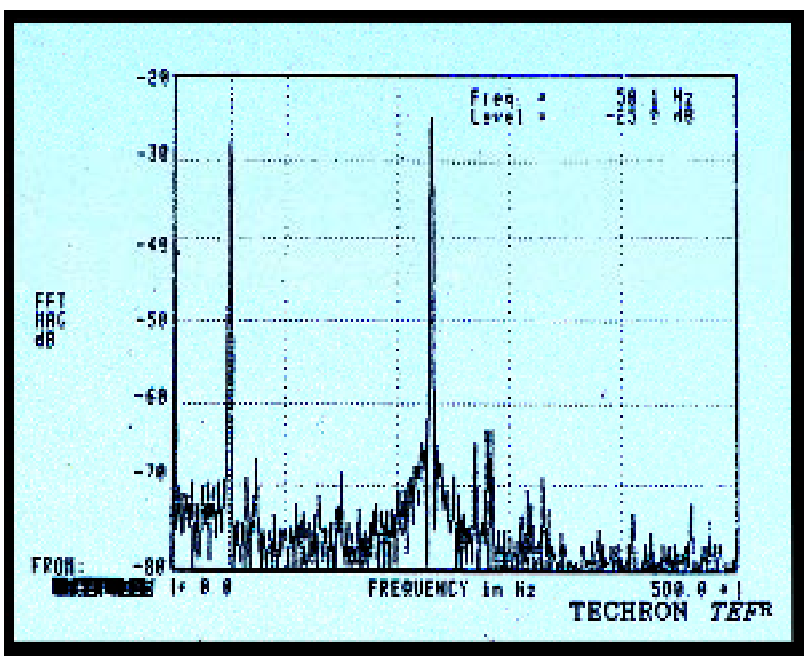
		2ND	3RD	4Th	5Th	6Th
120 dB						
VENT	2.0V	-49 dB	-55	<-55	<-55	<-55
HORN	1.9V	-43	-44	-53	<-55	<-55
125 dB						
VENT	3.7V	-53	-53	<-55	<-55	<-55
HORN	3.4V	-42	-47	-53	<-55	<-55
130 dB						
VENT	6.3V	-50	-48	<-55	<-55	<-55
HORN	5.9V	-39	<-50	<-50	<-50	<-50
135 dB						
VENT	11.5V	-37	-41	-48	<-55	<-55
HORN	10.5V	-36	-50	<-55	<-55	<-55
140 dB						
VENT	19.5V	-37	-35	-41	-52	<-55
HORN	19.0V	-34	-41	-53	<-55	<-55

Table 4

Table 4: The data for 70 Hz represents a region of apparent transition. Neither system is driven into a non-linear region and harmonic distortion components are again at about the same levels. Results from additional tests at 80 Hz and 200 Hz confirm this.



TOTAL DISTORTION OF A VENTED DIRECT RADIATOR WOOFER
50 & 230 Hz., 115 dB @ 2 METERS
FIGURE 3



TOTAL DISTORTION OF A FULLY HORN-LOADED WOOFER
50 & 230 Hz., 115 dB @ 2 METERS
FIGURE 4

MODULATION DISTORTION

		115 dB @ 2 METERS		120 dB @ 2 METERS	
		VENT	HORN	VENT	HORN
Fl	(50 Hz)	0 dB	0	0	0
F2	(230 Hz)	0	0	0	0
F2+F1	(280 Hz)	-26	-38	-27	-31
F2+2F1	(330 Hz)	-28	-44	-21	-39
F2+3F1	(380 Hz)	-36	<-50	-28	-44
F2-Fl	(180 Hz)	-28	-48	-25	-.36
F2-2F1	(130 Hz)	-41	-47	-30	<-50
F2-3F1	(80 Hz)	-40	-42	-36	<-50

Table 5.

Table 5: These measurements were performed with two frequencies (50 Hz and 230 Hz) playing simultaneously through each system under test. The tests were conducted at levels of 115 dB SPL and 120 dB SPL at a distance of 2 meters. The table and charts for modulation distortion clearly show that the HORN produces far less of this type of distortion; as much as 20 dB, or 90 percent, less. (Figures 3 and 4).

DISCUSSION

As mentioned, some believe modulation distortion is more objectionable than harmonic distortion [6]. Moir concluded modulation distortion to be the "predominant distortion in cone-type speakers" [7]. Other observers have disagreed. However, the LEAST POSSIBLE DISTORTION, no matter what the origin, is a primary design goal for any sound system. We could hardly think of accepting an amplifier that produced intermodulation distortion of several percent, and yet speakers that produce this much modulation distortion, or more, are common. Sound degraded by this form of distortion is described as "lacking clarity" or "not clean" [8]. The modulation distortion components produced by ALL loudspeakers are not harmonically related to the original program material and are therefore likely to be more irritating to the listener. Examination of the spectrum of acoustic musical instruments shows a compliment of harmonics along with the fundamentals. Musical instruments, in general, do not contain frequency modulation components.

Modulation distortion in loudspeakers is related to cone motion. For a given SPL, the input voltage to a HORN will be significantly less than that required by the VENT. Because the input voltage is lower for the HORN, the cone motion is lower. This results in lower distortion. The figures 3 and 4 confirm this.

In practice, it may be expected that the distortion levels encountered with direct radiator woofers will be GREATER than those shown in this article. This is due to the fact that the near-field measurement technique employed for these tests favors the smaller direct radiator. It should also be noted that the voice coil winding of the drivers used here is longer than those found in most of today's production models, allowing them to move farther before becoming non-linear. Driver parameters, such as this, play a crucial roll in controlling harmonic distortion.

CONCLUSION

As the motion picture industry enters the digital age, the subject of low frequency theatre loudspeaker distortion has been examined using modern enclosure constructions. The tests indicate that a properly designed HORN produces somewhat less overall harmonic distortion than a direct radiator. A serious investigation of speaker distortion must also include other types of distortion, particularly when they are greater in magnitude and not harmonically related. The tests of modulation distortion revealed that the HORN is clearly lower in this type of distortion when compared to a direct radiator. Both types of enclosures were tested using the same two 15 inch drivers.

We submit that these tests indicate that the direct radiator type woofer remains a compromise choice in theatre sound systems where a reduced cabinet size is chosen over high output and low distortion criteria. The dynamic range recorded with digital motion picture soundtracks, not to mention those encoded with the Dolby SR system or current 70 mm magnetic release prints, regularly requires theatre loudspeakers to produce levels exceeding 100 dB SPL in large spaces. To do this, loudspeakers with the greatest outputs and lowest distortion are indicated. These tests would seem to confirm that these attributes are most easily realized with the properly designed true HORN.

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8. G. L. Beers and H. Belar, op. cit.

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