EV THE PA BIBLE

ADDITION NUMBER FOURTEEN
LOUDSPEAKER SYSTEM TYPES

INTRODUCTION

In the third P.A. Bible addition the subject of microphone types was discussed. Like microphones, loudspeaker systems come in a variety of configurations. Previous P.A. Bible additions have briefly touched on loudspeaker system types. Addition 12, for instance, discusses vented type boxes for Electro-Voice FORCE loudspeakers and Addition 13 has a small section on cabinets. In this addition we wish to discuss the subject of loudspeaker system types in more detail in order to give some insight into this rather fundamental topic. We intend to concentrate mainly on the portion of a system that reproduces low-to-mid frequencies, as the geometry of this part usually determines the name given to the system type. This is probably natural, as in most cases the low-to-mid frequency section accounts for most of the systems bulk and weight.

This addition will also discuss the system design theories of Neville Thiele and Dr. Richard Small. You may possibly have encountered "Thiele and Small" in loudspeaker manufacturers' specification sheets, magazine articles on acoustics or the P.A. Bible itself. We will use some of this theory to help explain and sort out the performance characteristics of various loudspeaker system types. It is hoped that this material will help remove some of the mystery from loudspeaker system types and be of help in understanding the way they work, how they came about, and where they are most effectively used.

WHAT IS A SYSTEM?

A system of any sort is a collection or combination of things which form a coordinated and unitary whole. In the case of a loudspeaker system, the combination is the actual loudspeaker plus the enclosure in which it is put. The combination of these two elements should act together in the best possible way to achieve a desired performance goal in order to be classified as a good system. Putting an arbitrary loudspeaker into an arbitrary enclosure is not the way to achieve an optimized system. The knowledge of how to properly coordinate loudspeaker and enclosure in the best possible way is what the science of loudspeaker design is all about.

It is possible to achieve a good system by the familiar method of "cut and try". Such a method involves changing the variable elements of a loudspeaker and enclosure until a desired level of performance is obtained. However, if the system has any degree of complexity to it at all, it will be difficult to know when the desired result has been achieved in the best possible manner, thereby obtaining the desired performance in the least volume of space. In a loudspeaker system, basic performance goals usually translate into getting a specific low frequency limit (i.e., how low does it need to go) and efficiency level (the ratio of acoustic output to electrical input) from the least volume of occupied space. Effective space (and consequent weight minimization) is an important concept to keep in mind.

COMMON TYPES OF SYSTEMS

Over the years a variety of systems have been offered under various names. After stripping away the minor variations and multiple names, there are about six basic types that account for the great majority of systems on the market. These are:

1. dipoles (open-back baffles),
2. sealed boxes (acoustic suspension),
3. vented boxes (bass reflex, phase inverter, passive radiator),
4. horns,
5. combination boxes with horn midrange and vented bass sections, and
6. combination boxes with horn-bass and sealed-box midrange sections.

The names in parenthesis are some additional ones given to these types.

These system types are illustrated in Figure 1. Historically, horns are probably the oldest type of system. Early forms were megaphones and phonograph "morning glory" horns used to amplify stylus sounds in the days before electronic amplifiers. After the introduction of cone loudspeakers in the 1920's, simple open-back baffles, sealed and vented boxes and combination boxes evolved as various ways of allowing cone loudspeakers to reproduce sound effectively.

A few comments are in order to help distinguish the main characteristics possessed by these six types of systems.

Dipoles

This is the simplest type of system and, in its most rudimentary form, consists of a naked loudspeaker with the loudspeaker cone itself forming its own baffle! Due to its simplicity, it is a quite common type of system. It is found whenever a loudspeaker is mounted on a surface which has a substantial size opening on its backside. Examples can be found in open-back guitar amplifiers and dashboard-mounted car speakers. This opening allows the sound coming from the front and rear of the loudspeaker to interact and partially cancel each other at lower frequencies. This cancellation process begins to occur when the average baffle size is about half the wavelength of the sound being reproduced. A loudspeaker mounted on a 3-foot square baffle would allow cancellation to begin occurring at wavelengths longer than about 6 feet — a wavelength equivalent to a 190 Hz frequency. In general, it is hard to generate powerful low frequencies with dipoles because of the cancellation effect, although some forms of this system with rear cavities (see Figure 2) can produce mid-bass peaks. The rolled-off bass characteristic of this system type tends to make it "project" well. It is widely used in guitar amps.

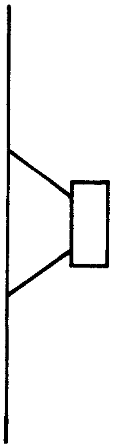
Sealed Boxes

This system type probably developed when someone tried to suppress the low-frequency cancellation inherent in a dipole system by closing off the system's rear. Sealing the box solved some problems and created others. It took until the 1950's for this type system to be sufficiently researched to allow the design of quality "bookshelf" systems for home use. These home systems offered smooth and extended low-frequency response in small-size boxes with rather low-efficiency levels of less than 1%. This type of system has tended to be used more for music reproduction in homes and background/foreground applications, than for musical instrument or fixed installation commercial applications.

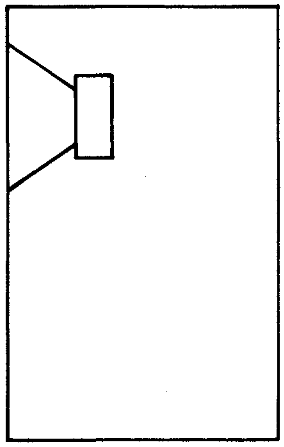
Vented Boxes

This system type appears to have been thought up in the mid 1930's. The basic idea was to put to work some of the acoustic energy that would otherwise be bottled up in a sealed box. To do this, the acoustic output from the rear of the cone needs to be phase inverted to compliment the output from the front of the cone over some appropriate range of frequencies. As it turned out, the proper coordination of all the variables of the box and the loudspeaker inside was a rather complex juggling act. Many of the early forms of this system type were uncoordinated to a degree that made listening to them unpleasant. One of the more common approaches was to attempt putting a vent on a system that worked reasonably well as a sealed system and getting either no noticeable improvement or (perhaps worse yet) a thumpy or boomy form of false bass. Figure 3 illustrates the nature of what has to happen in order to achieve usable response from this type of system. The variables of the box and the loudspeaker have to be coordinated so as to achieve a smooth net response from the combination of vent output and loudspeaker output. In essence, the vent acts as a second loudspeaker that takes over and reproduces the lowest frequencies — sort of a little sub woofer that automatically cuts in when needed. Thiele and Small were to describe this system type in great detail in the 1970's and show how to coordinate the loudspeaker and box to obtain smooth, usable response.

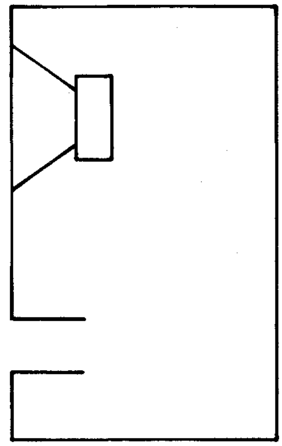
The vented system has become a widely used system type in musical



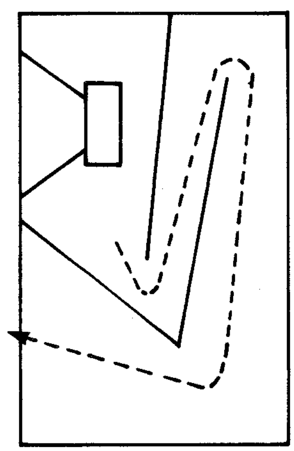
DIPOLE (Loudspeaker Mounted on a Finite Flat Baffle)



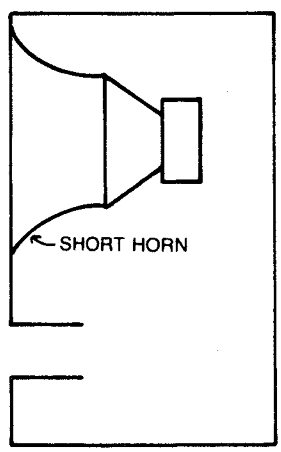
SEALED BOX



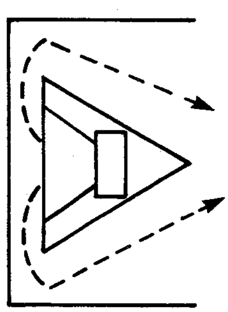
VENTED BOX

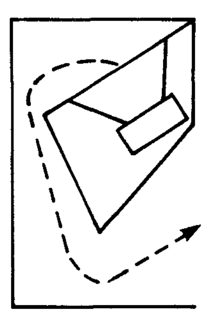


COMBINATION BOX (Horn Bass and Sealed Box Midrange)



COMBINATION BOX (Horn Midrange and Vented Bass)





HORN (folded - 2 methods shown)

FIGURE 1 — BASIC SYSTEM TYPES

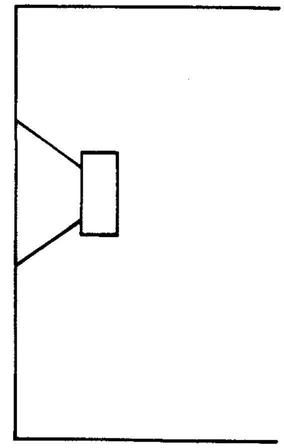


FIGURE 2 — Dipole with a Rear Cavity formed by Extended Sides.

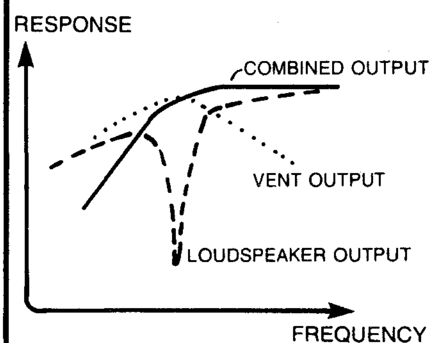
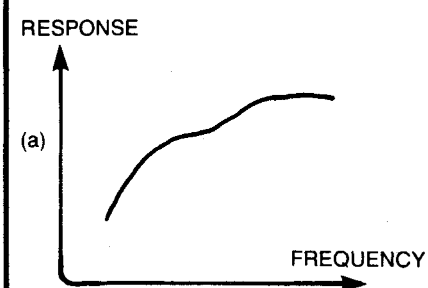


FIGURE 3 — How Loudspeaker and Vent Output Combine in a Vented System



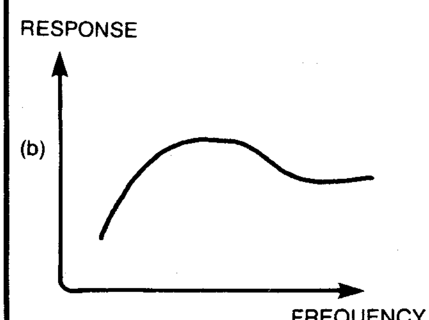


FIGURE 4 — Nature of Response of: (a) Combination Box with Horn Midrange (b) Combination Box with Horn Bass

instrument applications. It is capable of producing smooth, flat, "hi-fi"-like sound quality with good solid bass.

It is possible to install a properly weighted cone as a substitute for the vent in this system type. This vent substitute, or "passive radiator", duplicates the diameter of the vent it is replacing and has a weight equivalent to that of the air contained inside this vent. This type of system is, in reality, a minor variation of a vented system.

Horns

As noted before, this type of system is quite ancient. It was once used to amplify the feeble vibrations of the stylus on early phonographs, making these sounds audible to the listener. Horns usually possess the property of having very high conversion efficiencies — often in the 15 to 30% range. (When not horn-loaded, the highest efficiency obtainable from a single loudspeaker is in the 5 to 10% range.) Because of this, they were of special interest when the "talkie" motion picture appeared. Spacious motion picture theaters required relatively large amounts of acoustic output. Since early amplifiers had limited output, it was only natural that the inherently efficient horn system received considerable attention in the 1930's and 40's.

Horns that must reproduce low frequencies are rather large and lengthy devices, and it is common practice to fold them up in order to make a more compact package. Many possible folding geometries exist. Because of their long, expanding air columns, horns are relatively complex structures. The rate at which the horn's air column expands in going from the small (throat) end to the large (mouth) end is determined by the lowest frequency that the horn is expected to reproduce effectively. This frequency is referred to as the horn's "cutoff frequency". The horn ceases to operate well below this frequency and response drops off rapidly.

The main points to keep in mind when thinking of horn type systems are:

1. if properly designed, they can offer very high efficiency from a single cone loudspeaker used to drive them,
2. they tend to be large, and
3. they are of relatively complex construction.

Horns can produce tight, punchy, high-intensity sound.

Combination Boxes (Horn Midrange and Vented Bass)

In this form of system the box is subdivided into two sections which are not usually of equal size. One of the two sections is in the form of a short, horn-like structure with the loudspeaker at the rear or small end of the horn. As in the case of the vented box system, the very lowest frequencies come from the vents. Higher frequencies pass through the short horn but are relatively unaffected by it until the cutoff frequency of the horn is exceeded — typically somewhere above 100 Hz. Above this frequency, a combination of increased efficiency and greater directivity causes a response rise of three or four dB to occur. Figure 4a indicates the nature of this type of response. The change in both directivity and efficiency caused by switching from one type of system to another as frequency increases results in this form of shelved or stepped response characteristic. This rise in response can give a projected quality to vocals that many performers and engineers find effective.

Combination Boxes (Horn Bass and Sealed Box Midrange)

In this form of combination box, the tables are turned relative to the previous type. Here, bass is reproduced by the horn part. Almost all of the volume of the box is occupied by the horn in most cases. A small chamber houses the loudspeaker with the throat, or small end of the horn, beginning from an opening placed in this chamber. With this arrangement, frequencies between 100 and 300 Hz are radiated chiefly from the front of the cone, much in the manner of a sealed box type of system. The air chamber containing the loudspeaker acts as a shutoff valve for the horn above these frequencies. Lower frequencies are radiated from both the horn and also from the front of the loudspeaker. However, the higher efficiency of the horn tends to dominate the net low-frequency response. As might be expected, the response shape of this type of system favors bass over midrange in the manner illustrated in Figure 4b.

As in the case of the pure horn system discussed earlier, there are many possible schemes for folding up the large and lengthy horn. Several of these geometries result in the "scoop" type of appearance.

THE THIELE/SMALL CONNECTION

A selective discussion of the design concepts developed by Thiele and Small will help put the basic system types mentioned in better perspective. These concepts are basically a carefully reasoned way of coordinating loudspeaker, enclosure and, in some cases, auxiliary electronics so as to create pre-determined and desired low and midrange response curve shapes. These response curve shapes are given the names of the mathematical equations that describe them, hence Butterworth and Chebyshev responses of various kinds often appear in the description of systems which are based on Thiele and Small's work.

Even though Thiele's original work was titled "Loudspeakers in Vented Boxes"[1], sealed boxes are discussed as well, and Small's works are even more detailed in this respect. In the process of a thorough description of system possibilities, Thiele creates a table of 28 methods of achieving various selected responses from vented systems. This method of coordinating loudspeakers, boxes and (sometimes) auxiliary electronics are known as "alignments". In a sense, when all the significant speaker and box variables are aligned properly, the system produces the desired response. Small's work expands on Thiele's and, among other things, describes something that is best thought of as a system interrelationship equation which illustrates fundamentally important relationships between box volume, low frequency capabilities, conversion efficiency and system type.

This interrelationship equation is worth further discussion as it illustrates several very important matters about system behavior that no amount of wishful thinking will alter. It will help a user understand more thoroughly the implications of large and small systems, the problems of achieving higher levels of efficiency and more extended bass response and, finally, the ramifications of system type. Although the equation was meant to be applied to enclosed direct radiator systems, it can yield interesting information about horn systems as well. (Direct radiator is a term often given to systems where the loudspeaker directly addresses the air in the listening space.)

In its simplest form the equation is:

$$E = C\ V\ F^3\ K$$

where E is efficiency (the ratio of acoustic power out to electrical power put into the system),

C is a constant number dependent on the system of measurement used and the local environment the system is operated in,

V is the internal volume of the loudspeaker enclosure,

F is the frequency below which bass output begins to rapidly drop away, and

K is another constant number, but this time it is associated with the nature of the system response shape and, therefore, the system type. It is a very important number sometimes referred to as the "figure of merit".

Let us fix the system type for a moment so that K remains at a fixed value (think of it as having the value 1 if you wish) and look at a few revealing situations:

a) Extending the bass (making F smaller) makes severe demands on system design since F is multiplied by itself three times (or cubed). As an example, extending bass by one octave (making F one-half as large) would imply that efficiency would be reduced to one-eighth its former value ($\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$) if loudspeaker volume (V) were to remain unchanged. Another implication would be that if it would be desirable to keep efficiency (E) the same but extend bass one octave, then loudspeaker volume would need to be increased by eight.

b) Reducing the size of a larger system can certainly be done, but either efficiency would have to be reduced or low frequency capabilities would have to suffer or some combination of both things would have to happen. The equation must, in all cases, remain satisfied.

It should be understood that making system changes of the type being discussed would, in general, imply that the basic makeup of the loudspeaker (i.e., magnet size, moving system weight, etc.) used in the system would need to change in a manner prescribed by Thiele.

COMPARING SYSTEM TYPES

Now let us examine the situation involving a change in system type which implies that the K, or "figure or merit", in the system interrelationship equation is altered.

In one system of measurement, the value of the figure of merit (K) is between 1.5 and 2 for almost all sealed box systems that would have response curves that would be of interest. *Dipole systems* are somewhat more difficult to characterize due to their lack of a well-defined enclosure volume, but some recent work [2] suggests that K values for this system type appear to be less than 1. *Vented boxes* would usually have a figure of merit value between 3 and 4 although some unique forms of vented systems described by Thiele that use auxiliary electronics can be higher yet. These high values for the figure of merit are the reason for an upsurge of interest in vented box systems. As an example, consider a change in the figure of merit (K) from 2 to 4 obtained by designing a vented system instead of a sealed one. In this case, the efficiency (E) could be doubled, thus making it possible to obtain 3 dB more of sound pressure level from a system without having to increase enclosure size, sacrifice bass or get a larger amplifier. If a smaller box were to be desired, this same figure of merit doubling could be used to halve box size without other sacrifices. Electro-Voice has been interested in the potential of vented box systems since the early 1970's and currently offers systems such as the S-1202, S-1503, S-1803, FM-1202, FM-1502, and TL bass boxes that embody the values inherent in this system type.

Although the interrelationship equation is meant to be used with direct radiator systems, it is possible to derive a figure of merit for *horn systems* by doing measurements and deducing K. Some work in this area [3] suggests figure of merit values for horns are at best similar to those for sealed boxes. Because of this, most of the comments made in comparing vented to sealed boxes would apply to horns as well. What about the matter of high efficiency? It is known that horns can have efficiency levels in excess of 10% but that single direct radiators seldom exceed 5 to 7%. The interrelationship equation suggests that putting several of the same systems close together is, in effect, increasing the box volume (V) and thereby increasing efficiency. This method can be used to push the net efficiency of direct radiator systems to values above 10%. The point being made here is that very high efficiencies are not the exclusive domain of horn-type systems. They can be achieved with direct radiator systems by using several closely spaced loudspeakers.

The *combination box with horn midrange and vented bass* is sometimes constructed so that the vented box portion of the system is most of the box. In this case, the comments made about vented boxes are applicable to this type of system. However, when the short horn takes over (usually somewhere above 100 Hz), the response will show a rise. This rise is due to a combination of directivity increase and some efficiency increase. The sonic balance caused by this type of response is sometimes favored. The Electro-Voice SH-1502 is a system of this type. If, however, this system type is constructed so that the horn portion of the box is a dominant part of the total system volume, then the system will behave more like a pure horn with a resultant reduction in the figure of merit.

The *combination box having horn bass and sealed midrange* is basically a horn system with a small section of the box apportioned to the chamber containing the loudspeaker. Because of this, the comments made about horns as compared to direct radiators apply to this system type, with the only appreciable difference being that the loudspeaker, which faces outward, provides some subdued midrange output.

SUMMARY AND APPLICATION COMMENTS

Six basic types of loudspeaker systems have been described in this P.A. Bible addition that range from simple, open-back baffles (dipoles) to quite complex horn-type systems. Within each system type there can be a variety of ways to balance or "voice" the sound quality of the system. However, there are some general sonic characteristics or "signatures" that can be assigned to each type that make them more suited to certain applications. The following table should be of help in summarizing the situation.

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TABLE OF CHARACTERISTICS OF LOUDSPEAKER SYSTEM TYPES

System Type	Figure of Merit (K)	Complexity of Construction	Typical Response Shape	Characteristic Sound Quality	Typical Use
Dipole (Open-Back Baffle)	Less than 1	Very Simple	Strongly rolled off bass due to cancellation	"Projects" well	Guitar Amplifier
Sealed Box	1 5 - 2	Simple	Can be flat or have bass somewhat rolled off	Tight sound punchy midrange	Guitar Amplifiers, some vocal
Vented Box	3 - 4	Simple	Usually Flat	Smooth "Hi Fi" character with solid bass	Floor monitors, vocal, bass
Horn	1 - 2	Very Complex	Can be flat or have bass somewhat rolled off	Tight, punchy midbass	Low Frequency building block for large systems
Combination Box (Horn Midrange)	3 - 4 (If horn is a small part of the box)	Complex	Response rise when horn takes over	Good projection	General use, Especially Vocal
Combination Box (Horn Bass)	1 - 2	Very Complex	Elevated Bass	Strong Bass Emphasis	Bass Instruments (Drums, Organ)

REFERENCES

[1] A.N. Thiele, *Loudspeaker in Vented Boxes: Part I,* Journal of the Audio Engineering Society, Vol. 19, pp. 382-392 (1971 May); Loudspeakers in Vented Boxes: Part II, ibid., pp. 471-483 (1971 June).

[2] R.J. Newman, *Dipole Radiator Systems,* Journal of the Audio Engineering Society, Vol. 28, pp. 35-39 (1980 Jan./Feb.).

[3] D.B. Keele, *An Efficiency Constant Comparison Between Low-Frequency Horns and Direct-Radiators,* presented at the 54th Convention of the Audio Engineering Society (May 4-7, 1976).

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