Boundary Effects and Loudspeaker Design

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Background

The use of a purely analytical model to describe the details of a loudspeaker's acoustic performance is so cumbersome as to be practically impossible. Unfortunately, there are very few closed-form acoustic equations that are of much use to a loudspeaker designer. Even though the acoustic wave equation,

$$\Delta^2 p - 1/c^2(\vartheta^2 p/\vartheta t^2) = 0$$

is compact, its solutions are generally not expressible in such a simple form. Solutions to the wave equation depend, in general, on two components: source terms and boundary conditions. A number of rudimentary source models are employed for instructional purposes in texts on acoustics. These include a spherical source with radial motion (a "breathing" sphere) and a flat circular piston. Boundary conditions often used for textbook analyses include infinite baffles, semi-infinite cylindrical tubes, and semi-infinite horns of various shapes. Even with these simplifications, the mathematics required to solve acoustic radiation problems are nontrivial. Additionally, as useful as the simplified models are in gaining an understanding of elementary acoustics, they offer little in the way of detailed predictive capability to a loudspeaker designer.

Most of the difficulties in predicting the specifics of a loudspeaker's behavior are caused by boundary conditions. The shapes of real-world transducers, horns, and loudspeaker enclosures are sufficiently complex that they cannot be accurately represented in concise mathematical forms. The task of accounting for complete information about the various boundaries present in a loudspeaker is a daunting one. Even with the availability of computer-based finite element analysis, data entry alone can easily take more time than the construction of a prototype for testing.

While it is impractical to predict analytically the exact acoustic behavior of a real loudspeaker, it is possible and desirable to develop a feeling for the likely effects of various loudspeaker boundary features. Even if we are designing a system entirely by trial and error, having some insight into the effects of acoustic boundaries can be of great value in diagnostic and development work.

Types of Boundaries

Most of the boundaries associated with loudspeakers are made of reflective surfaces: enclosure walls are designed to be rigid and generally have hard surfaces. The same is true for horn surfaces. Phenomena associated with this type of surface fall into two broad categories: reflection and diffraction.

In the simplified textbook models such as a piston radiating into a half space, the infinitely large baffle on which the loudspeaker is mounted is assumed to be perfectly reflective. All “reflections” that occur at this surface, however, will add coherently to the outgoing wave caused by the source, since the source is in the same plane as the baffle. The only interfering radiation present in this model is caused by the source itself, and it is this simplicity that allows a closed form solution - the piston directivity function - in the piston’s farfield.

If a hard surface is present on the front of the infinite baffle - as would be the case with room walls, for example - the wave's outgoing motion can continue no further past this surface. Its direction is reversed due to *reflection.*

In a typical direct radiator loudspeaker, the wave created by a transducer expands along the front surface of the cabinet until it reaches the edges. At these edges, the support provided by the enclosure's front surface for forward motion of the wave abruptly collapses as the wave is allowed to expand rearward as well as forward. The propagation of the sound wave past this point is governed by *diffraction.*

Loudspeaker cabinet diffraction has not been a well-understood phenomenon until relatively recent work [1]. The model developed by Vanderkooy shows that diffraction at an edge has strong dependence on the observation angle, and that forward diffraction (in the same direction as the original outgoing wave) is inverted in polarity, whereas diffraction at angles greater than 180 degrees (to the rear of the loudspeaker) is of the same polarity. The reader is encouraged to study Vanderkooy's work, as well as the other references, for mathematical treatments of this phenomenon.

A Brief Empirical Investigation

From the preceding discussion, it seems apparent that energy diffracted from cabinet edges and other transitional features on a loudspeaker will arrive some time after the "direct" wave from the transducer. In addition, diffracted energy moving in a forward direction will be reversed in polarity from the primary wave. These two circumstances - delayed arrival and reverse polarity - obviously lead to the possibility of interference between the primary wave and arrivals caused by diffraction effects, with a resulting degradation in response. The easiest way to verify such a hypothesis is to perform some simple controlled experiments.

The effects of diffraction from panel edges are illustrated in the following graphs. On axis response measurements were performed on a 1 inch soft dome tweeter with a 3.75" (95mm) square mounting panel. Fig. 1 is a response measurement of the tweeter alone, suspended from a microphone stand. Fig. 2 is the same tweeter mounted on a thin panel approximately 19" (483mm) square.

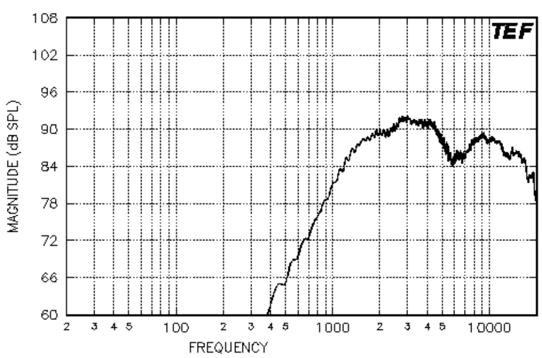

Fig. 1. *Dome tweeter on axis with no baffle*

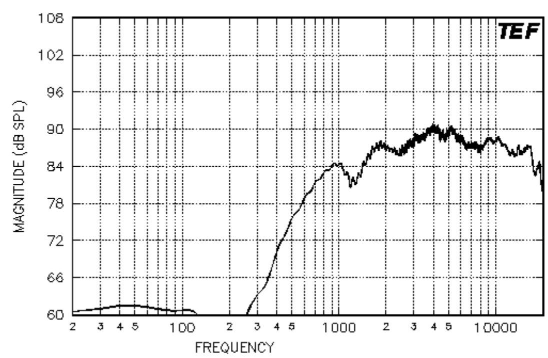

Fig. 2. *Dome tweeter on axis with 19" square baffle*

Note the relatively wide depression in the tweeter's response in Fig. 1. The center of the depression is approximately at 6.5kHz. A diffracted arrival at a one-wavelength distance will interfere destructively with the primary wave. At 6.5 kHz, this distance is approximately 2.1 inches. This is consistent with the average distance from the center of the tweeter mounting flange to its edge. A tweeter with a round mounting flange could be expected to have a deeper, narrower notch due to reduced time smear in the diffracted arrival.

The same characteristic notch is present in Fig. 2, but at a much lower frequency. This is also consistent with the model of reverse polarity forward diffraction: The notch is now centered at 1220 Hz, which has a wavelength of approximately 11 inches. The average distance from the center of the 19" panel to its edge matches this dimension very closely.

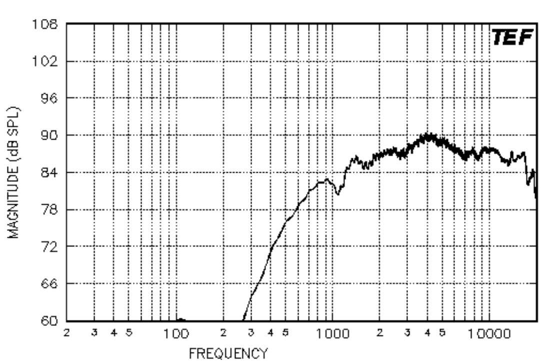

Fig. 3. *Dome tweeter on baffle with edge absorption*

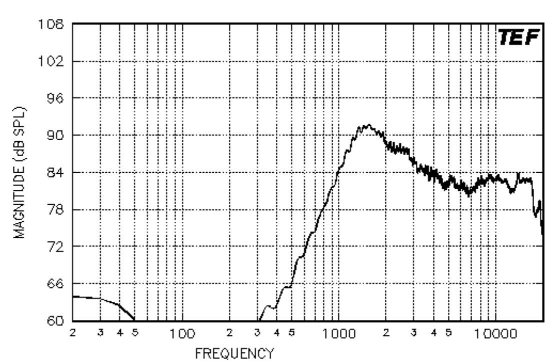

Fig. 4. *Dome tweeter, no baffle, absorption on flange*

Fig. 3 is the same as Fig. 2 with the addition of a layer of 3/4" (19mm) thick foam attached at the edges of the panel. This material is relatively absorptive above 1500Hz, less so at lower frequencies. Clearly, it is incapable of absorbing all of the radiation that diffracts at 1200Hz, although the response does improve slightly at this frequency. Finally, Fig. 4 shows a measurement taken on the tweeter alone; in this measurement, the mounting panel was covered with foam, with a cutout in the center so as not to block direct radiation. Once again, the frequency dependence of the foam's absorption is evident. What is surprising is the reduction by almost 6 dB in apparent sensitivity above 3kHz. Clearly, the mounting panel is sufficiently large to create an approximate halfspace acoustic load at higher frequencies. The absorptive material eliminates this support.

Figs. 5-8 illustrate some effects of edge diffraction from the edges of a horn mouth. The measurements were performed on a high frequency horn driven by a 1 inch exit compression driver. Two measurements were taken on each of two configurations: one on axis and another approximately 20 degrees off axis.

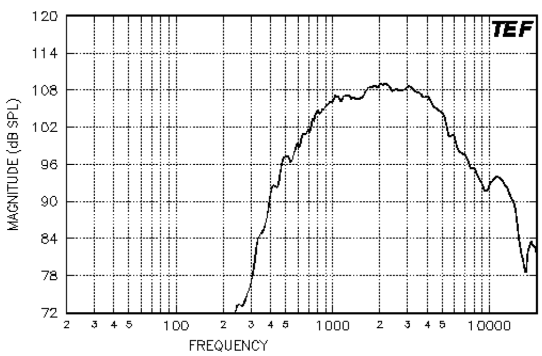

Fig. 5. *High frequency 60 x 40 horn on axis*

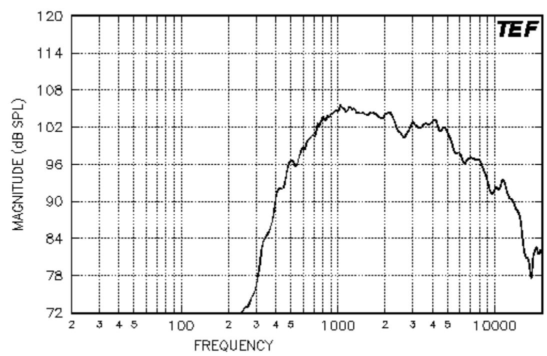

Fig. 6. *High frequency 60 x 40 horn approx. 20 degrees off axis*

Figs. 5 and 6 show the response of the horn/driver combination with no acoustic treatment. Figs. 7 and 8 are measurements of the same driver on an identical horn that has had acoustic absorption (open-cell foam) glued to the periphery of its mouth.

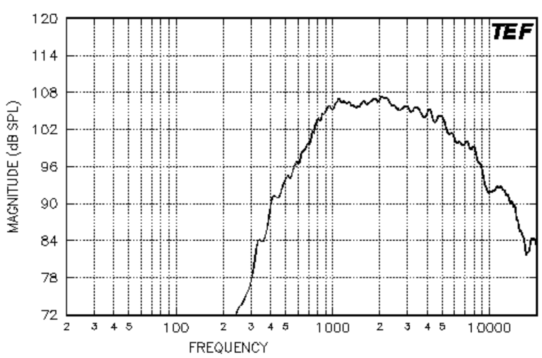

Fig. 7. *High frequency 60 x 40 horn with absorption, on axis*

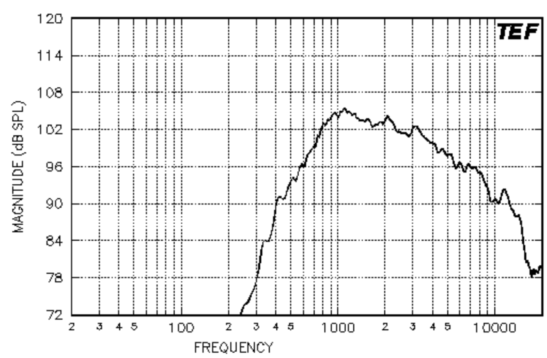

Fig. 8. *High frequency 60 x 40 horn with absorption, off axis*

As a means of examining more closely the effect on directivity of horn mouth diffraction, Figs. 9 and 10 show normalized responses of the treated and untreated horns, respectively.

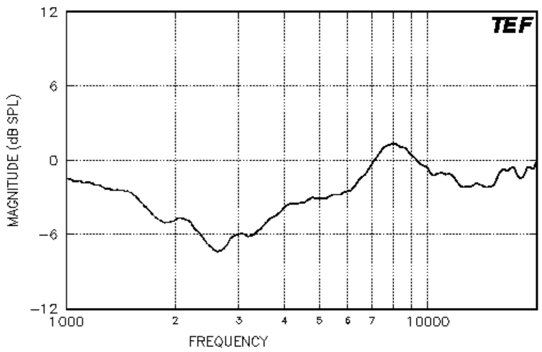

Fig. 9. *HF horn normalized off axis response, no absorption*

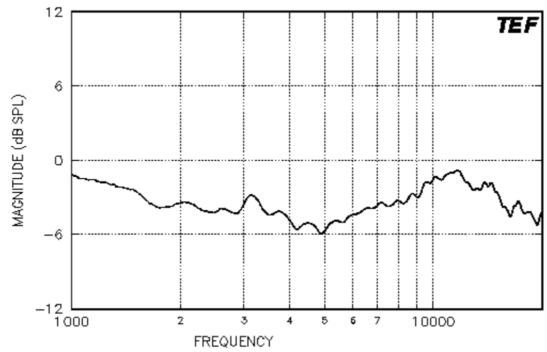

Fig. 10. *HF horn normalized off axis response with absorption*

Note the improvement in directivity vs. frequency in Fig. 10. The total window of variation in the normalized off axis response has been reduced by approximately 4 dB, and the apparent narrowing of the horn's horizontal pattern between 2 and 3kHz turns out to have been largely caused by interferences resulting from mouth diffraction. It is clear from this experiment that diffracted radiation can play as great a role in the directional behavior of a horn as the horn's sidewall angles.

Implications for Loudspeaker Design

This discussion of loudspeaker boundaries is intended to be indicative rather than exhaustive. A number of implications for loudspeaker design are apparent:

1. Transitions in the shape of a loudspeaker (e.g., edges, slots) behave themselves as acoustic sources. Arrivals from these features always follow the primary wave in time. Additionally, they are often reversed in polarity.

2. Strategically placed acoustic absorption can be a useful diagnostic tool in loudspeaker development.

3. The shape of a horn, by itself, does not entirely govern the horn's directivity. Diffraction from the mouth and from intermediate transitions can play as great a role in both response and directivity as the interior shape of the horn.

References

[1] John Vanderkooy, "A Simple Theory of Cabinet Edge Diffraction," J. Audio Eng. Soc. (1991 Dec.)
[2] J.R.Wright, "Fundamentals of Diffraction," J. Audio Eng. Soc. (1997 May)