Comments On Half Space

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What is the effect on the response of a loudspeaker when it is placed in half space? I have noticed widespread misunderstanding of this very fundamental acoustical phenomenon, even amongst expert practitioners. I believe the reason for the confusion is not intellectual laziness or misinformation, but *inadequate terminology*. The problem is that not all half spaces are created equal. One could argue, ironically of course, that some half spaces are more equal than others.

The clearest path to understanding half space loading that I know of, is the principal of virtual images. Mixing efficiency, directivity, and pressure superposition in the same analysis will surely lead to confusion. In fact, both directivity and efficiency changes are largely consequences of superposition, rather than additional factors. All that is required for an intuitive understanding of half-space loading is mirror image analysis.

Examples

Let's start with the simplest case: a point source located at the surface of a boundary. The sound that would have propagated downward in the figure below is instead reflected upward. The contribution of the source combines perfectly coherently with the contribution from the mirror image, because they are located in the same place. The result is a doubling, or 6 dB increase in pressure, everywhere above the plane.

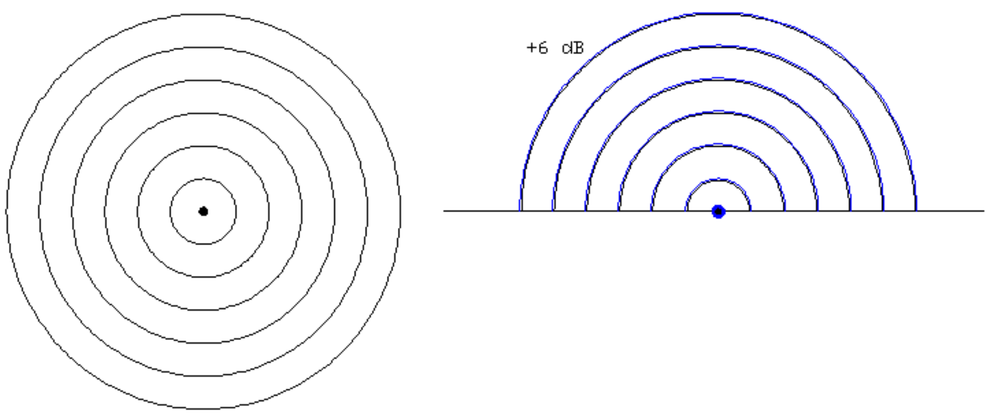

Figure 1

To make this example one step more complicated, let's move the source a small distance above the plane. Then, the combination will be much less coherent. However, at point "A" there is still coherent summation, so the response will be 6 dB higher at all frequencies. At point "B", on the other hand, the response will vary with frequency – exhibiting the classic comb effect curve shown below. Interestingly and importantly, the position of the acoustical source and microphone can be exchanged and the resulting response will be identical. For example, if either the source or the microphone is on the boundary (or both), the response will be +6 dB at all frequencies. This is one example of the principle of *duality* in acoustics.

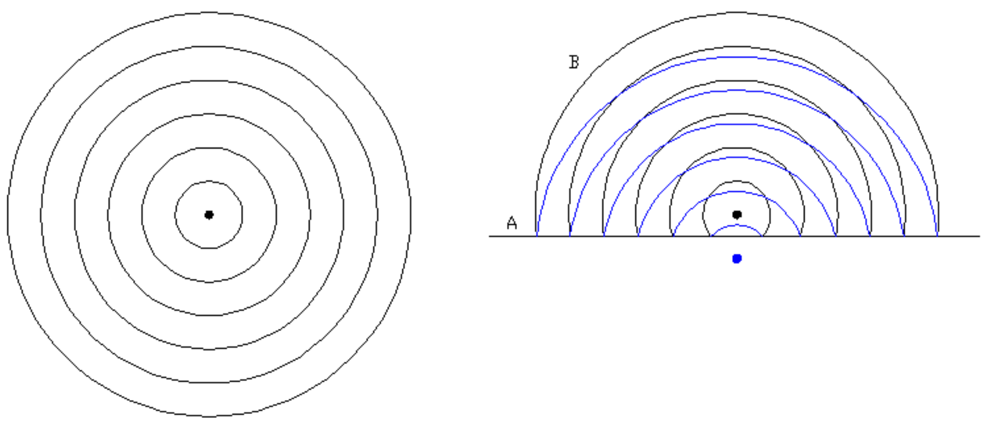

Figure 2

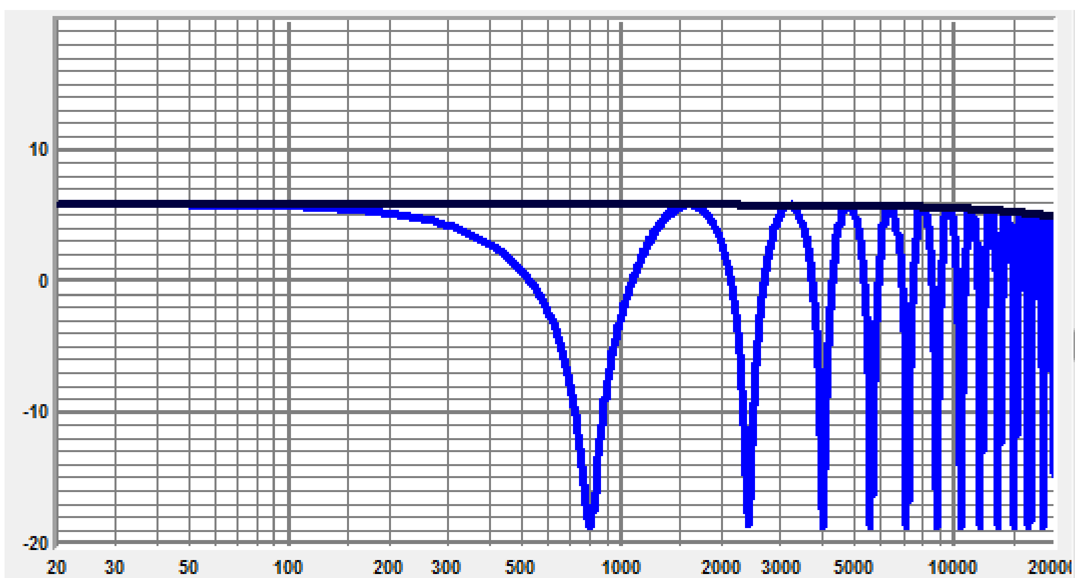

Figure 3

These examples may be interesting from an analytical point of view, but loudspeakers are most definitely not point sources. It's when the source has frequency dependent directionality that things get interesting. It's also when it becomes apparent that the expression, "half space", by itself, does not carry enough information to denote the environment.

Let's look at the mirror image of a schematic directional loudspeaker. Low frequency radiation is shown in black, and high frequency radiation is shown in red. If the directional loudspeaker is located on the boundary and aimed parallel to it, then both the low frequency and high frequency pressure is doubled everywhere, due to the presence of the boundary.

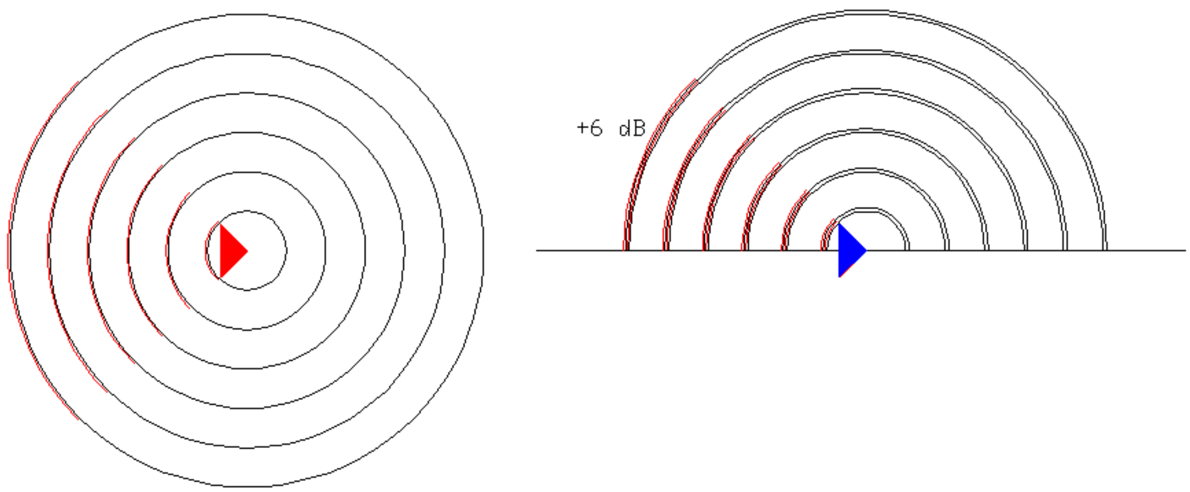

Figure 4

If, however, we aim the loudspeaker away from the boundary, then the high frequency output of the image, or reflected, loudspeaker never arrives on the "real" side of the boundary. The low frequency pressure doubles, but the high frequency pressure isn't changed at all by the presence of the boundary. Obviously, a surface cannot have an effect on sound that doesn't strike it.

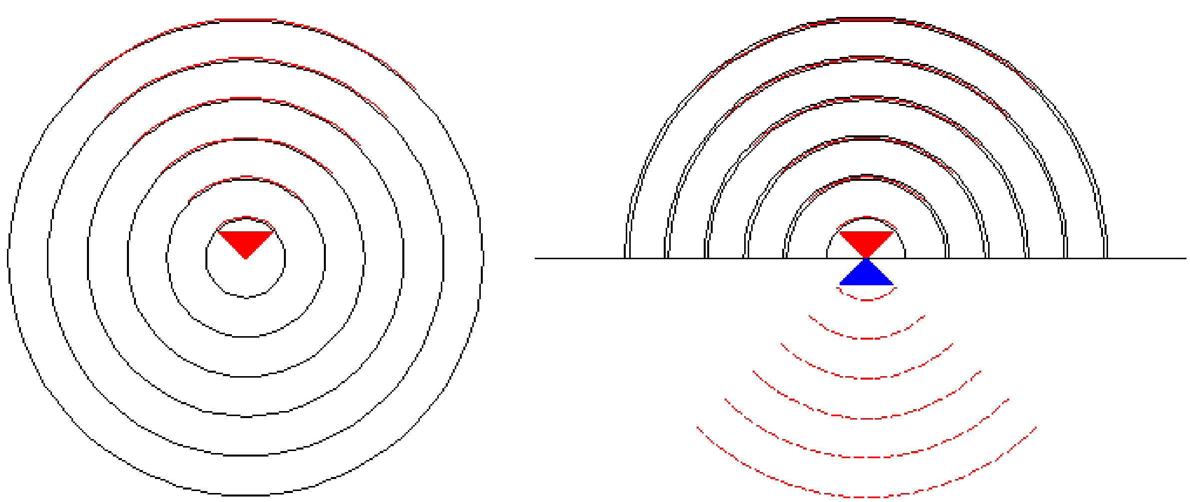

Figure 5

The net effect of a boundary such as this is to change the shape of the frequency response. Low frequencies increase in level, while high frequencies do not. The frequency response chart below represents a model of a real, measured, loudspeaker (a 15-inch two-way, horn-loaded loudspeaker), and its mirror image. The real speaker's response is shown in red. The mirror image, or virtual, speaker's response is shown in blue, and the superposition of the two is shown in green.

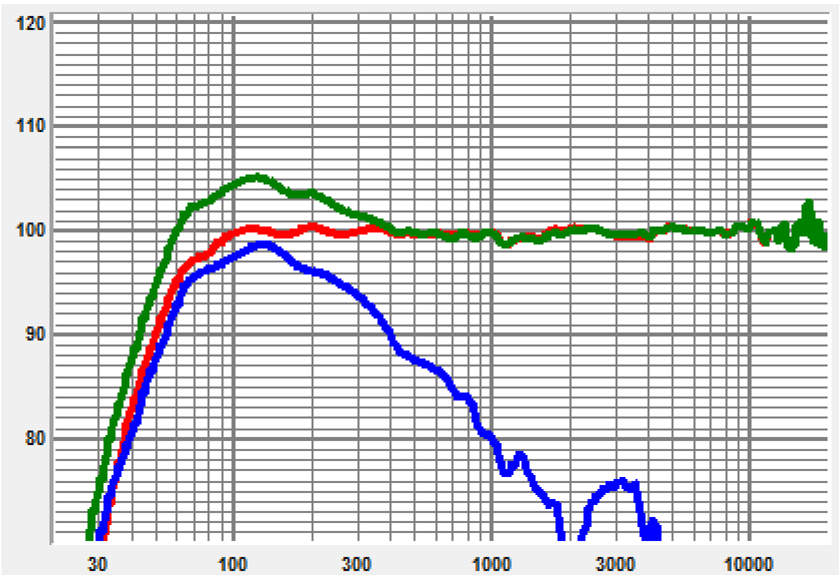

Figure 6

This model is useful, because it illustrates the "bass buildup" that occurs when a loudspeaker is soffit mounted. A more common form of half space loading is a bookshelf, or wall mounting. In that case, the backward propagating bass will still reflect forward and combine with the direct radiation. However, the real and image sources will no longer be co-located. The image source's contribution is delayed, relative to the real source. This results in the comb effect shown below. In this example, the source is located 38 cm (15 inches) from the boundary, to represent a small loudspeaker enclosure backed up to a wall. As you can see, the "coupling" of the loudspeaker with the wall has complex ramifications, but only at low frequencies.

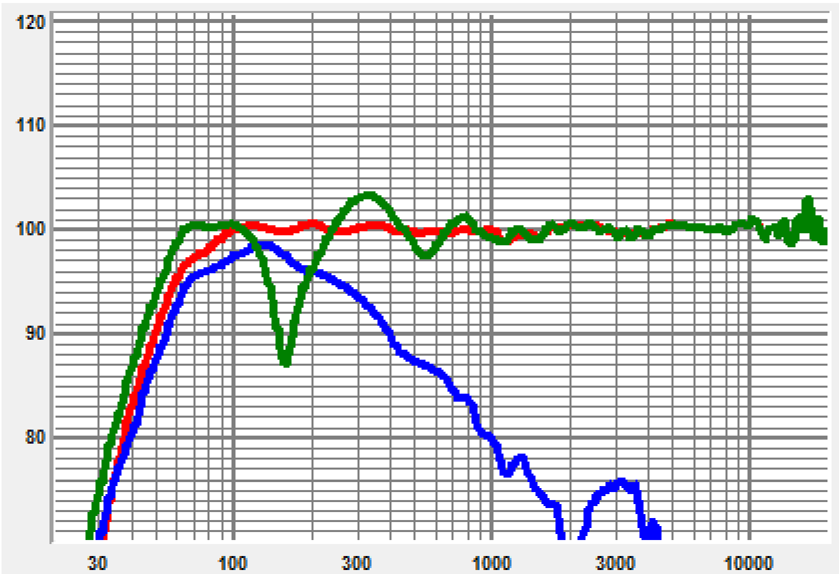

Figure 7

If the same loudspeaker is aimed parallel to the boundary (as in Figure 4), or placed next to an identical loudspeaker facing the same direction, the axial response will increase by 6 dB at all frequencies. This is represented by the red & green curves in the figure below. Off axis, however, the response displays the comb effect seen in Figure 3. The blue curve in Figure 8 is the response of a single loudspeaker, 90 degrees off axis; while the violet curve is the combined response of a pair of loudspeakers, or a loudspeaker and its reflection.

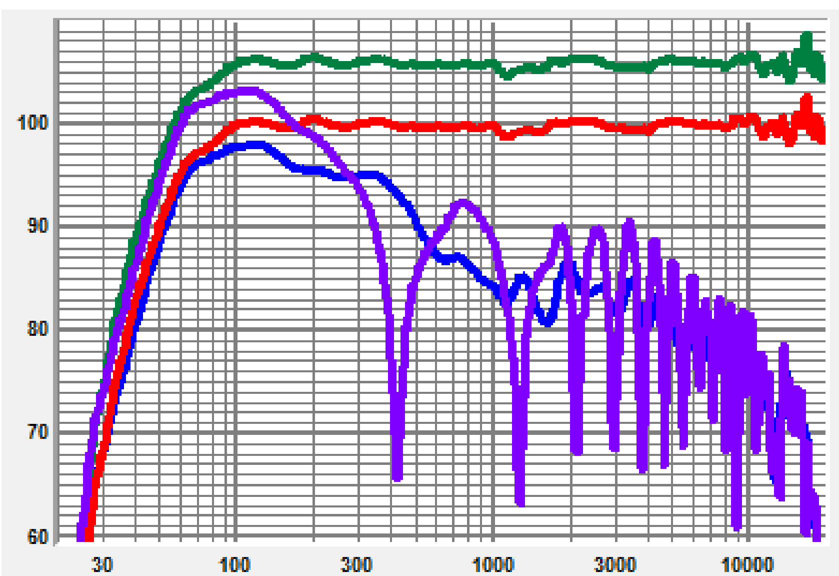

Figure 8

Subwoofer Deployment

The topic of half-space loading often comes up in the context of subwoofer placement. When a horizontally aimed loudspeaker is placed on a horizontal surface, the reflected radiation adds coherently to the direct radiation at all frequencies, and in all directions (as in Figure 3 and Figure 8). No matter where the listener is located, he will hear a 6 dB louder signal than he would have heard if there was no floor. Likewise, if the listener is located at the boundary, he will hear a 6 dB louder direct signal than he would have heard if there was no floor – regardless of where the subwoofer is located (as in Figure 2, with the listener located at position "A").

Isn't that interesting? As long as the listeners are on the floor (not such a stretch), the sound pressure is the same at a given distance, whether the subwoofers are on the ground or flown. That seems to contradict the well-known fact that placing subwoofers on the ground increases their efficiency by 3 dB. Actually, there is no contradiction. Look at Figure 2 again. The pressure increase at position "A" is +6 dB, regardless of the distance of the source from the boundary; but, the pressure increase perpendicular to the boundary varies between + 6 dB and -∞ dB. On average (in a power sense), the pressure increases by 3 dB. If the source had been on the boundary, the pressure would have increased by 6 dB everywhere. So, there is a net increase in the radiated power of 3 dB when a source is located sufficiently close to a boundary.

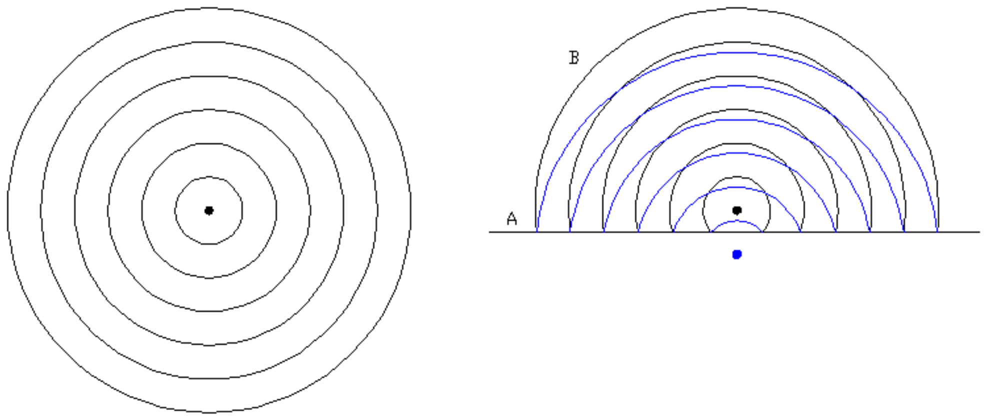

Figure 9 (Same as Figure 2)

The interesting thing to notice is that all of the extra power generated by placing the loudspeaker on the ground goes *up*, away from the floor. There is no increase in the direct pressure at the listener (assuming he is on the same floor), but more sound power is driven into the ceiling, from where it will eventually join the reverberant field. So, the fabled "coupling to the floor" is really "driving the reverberant field harder".

The real benefit of ground stacking has to with the fact that listeners' ears are not typically *on* the floor, but four or five feet above it.   If the speakers are elevated above the floor, 45 degrees above horizontal from the listeners' perspective, the ground bounce will produce its first comb effect notch at about 80 Hz. If the elevation angle is 30 degrees, the first notch moves up to 113 Hz. If the subwoofers are on the floor, then propagation is parallel to the floor, and there is no ground bounce. Hence, there is no comb effect.

Efficiency/Loading

Another acoustical fundamental that the above analysis may seem to contradict is the idea that mutual coupling changes the nature of a source. The presence of a boundary surface or an identical loudspeaker results in a change in the mass loading (the effective mass of the air in front of a diaphragm), as well as the acoustical resistance (the resistance to diaphragm motion presented by the air). An increase in efficiency implies an increase in the acoustical resistance.

At some point, doesn't the change in the acoustical load have to change both the strength of the source and the shape of its frequency response (since its resonance will have shifted)? That would imply that superposition is not enough – or that we also have to consider the change in the system, due to mutual coupling.

The answer is both yes and no. Superposition predicts how a system will change when *a second drive signal* is engaged. Measure the response with one source driven. Measure the response with a second source driven. Measure the response with both sources driven. The response with both sources driven will be exactly the same as the complex sum of the response to each individual source – as long as both sources were present in all three cases. If the second source was not physically present when the first source was measured, then the conditions for superposition were violated because the *system* was changed, not just the drive signals. The first source experienced two different acoustical environments.

Superposition does not predict how a system will change when *a second source* is introduced to the environment. A non-energized second source may affect the response of a first source: it may decrease the sound pressure by passively absorbing energy (especially at resonant frequencies), or it may increase the sound pressure by replacing nearby air with immobile, incompressible matter (referred to as "baffling").

The interesting observation is that it's actually very easy to determine if coupling will change the nature of a source significantly. Just introduce a second identical source, but don't turn it on! If being coupled with the second source changes the nature of the first source, it will be apparent in the measured response of the first source, when the second source is introduced. This technique allows the acoustical loading to be assessed separately from the summation of the sources.

The moving mass of direct radiating loudspeakers is typically quite large, relative to the effective mass presented by the air. Consequently, the presence of a boundary or additional loudspeakers has a very small effect on the motion of the cone. For most purposes, only superposition must be considered - acoustical loading can be ignored.

A horn subwoofer with a small mouth may not load well at very low frequencies due to the strong reflection returning from its mouth. Adding more units or placing them near one or more boundaries increases the acoustical load seen by the mouth, and reduces the strength of the reflection. Consequently, the shape of the response curve may change significantly at low frequencies, when multiple units are employed.

Conclusions

The effect of a half-space boundary on the response of a loudspeaker depends on whether it is parallel to the main axis of radiation (like the floor or a sidewall) or perpendicular to it (like the wall behind a bookshelf speaker). An axis-parallel boundary increases the axial response by 6 dB at all frequencies, while an axis-perpendicular boundary increases the very low frequency response by 6dB, but may not increase the high frequency response at all. In both cases, any physical separation from the boundary results in frequency response combing in the direction perpendicular to the boundary.

When the response of a subwoofer is specified for half-space, one can assume an axis-parallel surface is implied (the floor), and that the shape of the response is nearly the same as the anechoic response, but 6 dB higher. The shape of the response of a direct radiating subwoofer will not change significantly if it is placed in full space, rather than near a boundary – unless the design is unusually sensitive to loading conditions.

When a studio monitor has a "half-space loading" switch that applies a low frequency shelving filter, one can assume that it should be used whenever the speaker is close to an axis-perpendicular boundary.