GROUND PLANE ACOUSTIC MEASUREMENT
OF LOUDSPEAKER SYSTEMS

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Elaborate electronic techniques or specially constructed environments are usually required to measure only the direct field from a loudspeaker without contamination from reflected signals. By placing the measurement object on a rigid, unobstructed ground surface, and placing the measurement microphone flush with the ground, an accurate simulation of the anechoic response of the object together with its image source may be obtained.

INTRODUCTION

When measuring the sound output of a loudspeaker, it is usually desirable to separate the direct sound field produced by the source from the reverberant field generated by the reflections in any particular environment. This has traditionally been accomplished by placing the loudspeaker source in an artificial free-field environment, an anechoic chamber, specially constructed for this purpose. This provides accurate measurement conditions for mid and high frequencies at small measurement distances; however, the finite size of the chamber necessarily limits low frequency accuracy and large measurement objects and long measurement distances also decrease the usefulness of such environments.

Another approach to simulating a free field is to suspend the source up in the air, far enough above the ground to eliminate significant reflections. This is awkward at best, particularly for large measurement objects and long measurement distances. Near field measurements may be taken, but they are accurate only for the low frequencies.

Recently, gating and other delay techniques have been developed to extract the direct field from the total output through an adjustable time window, but these require complex manipulation of elaborate electronics and still suffer from bandwidth restrictions at low frequencies.

The previous approaches try to remove the affect of the environment entirely from the measured signal. Another approach is to stabilize the environment, such that any effect introduced by it can be easily qualified. The most common example of this is the hemispherical free-field, where the front surface of the loudspeaker is mounted flush with a large baffle surface, changing the effective radiation volume from a solid angle of 4π steradians to 2π steradians. This method has been adopted in order to better simulate the low frequency load on a loudspeaker in typical use conditions [1, p. 460], but also allows somewhat less complexity in the measurement environment. The 2π baffle may be surrounded by the wedges of an anechoic chamber, or it may be generated by placing the loudspeaker in a pit flush with a hard ground surface, the unobstructed open air providing the hemispherical free-field. In either case, the change in integrating area provides a different, but stable and known environment in which to assess loudspeaker performance.

In the same way that we can change the low frequency loading and still extract the necessary information, we can allow a single reflection if its effect can be accurately predicted. In the presence of boundaries where drastic changes in acoustic impedance occur, acoustic image sources can be employed to model the resulting wavefronts. The method of images has been utilized extensively in underwater acoustics [2, p. 427, 474] and in the field of aircraft noise [3, p. 15]. If a loudspeaker is mounted resting on a smooth, rigid ground surface and the mic is placed flush with the ground, a mirror image can be thought of as being produced below the ground surface next to the real source. The presence of the image source effectively doubles the axial pressure, adding 6 dB to the SPL. The measurement then approximates two identical loudspeakers next to each other in free space. Figure 1.

THEORY

A spherical sound source radiating uniformly in all directions close to a rigidly reflecting boundary may be considered to be a pair of sources in a free field vibrating in phase and equal in strength, due to the presence of an image source beyond the boundary. This is shown in Fig. 2.

From Beranek [4, p. 92-96] the equation for the magnitude of the rms sound pressure $|p|$ is:

$$|p| = \frac{2A}{r}\left|\frac{\sin[(2\pi b/\lambda)\sin\theta]}{2\sin[(\pi b/\lambda)\sin\theta]}\right|$$

Where A is the magnitude of the rms sound pressure at unit distance from the center of each source, b is the distance separating the sources, r is the measurement distance, and θ is the angle to the perpendicular bisecting the sources. At low frequencies b is very small compared to a wavelength and the two sources essentially coalesce. The pressure at any distance r and at any angle θ is then double that for one source acting alone.

As the wavelength decreases with increasing frequency, the pressures arriving from the two sources will be different in phase at various angles, forming changing directivity patterns. The axis bisecting the sources, $\theta = 0^\circ$, is the principal lobe of the directivity pattern, however, and the pressure on this axis is always double that without the boundary and image source. This doubling of the pressure will add 6 dB to the axial SPL. It is important to remember that while we have doubled the pressure and generated four times the intensity, the power generated has only doubled. Olson's chart is useful in understanding these differences [5, p. 32; 6, pg. 13].

PRACTICAL MEASUREMENT CONSIDERATIONS

The most appealing aspect of the ground-plane measurement technique is that the only special environment necessary is a large, flat, smooth and rigid (reflective) ground surface. Any asphalt or concrete parking lot or playground field, free from obstructions, can be utilized. There should be no obstructions in any direction for a distance which will depend on the measurement distance and signal frequency. For guaranteed safety, the distance from the source to any obstacle large compared to a wavelength should be at least five times the measurement distance, insuring that worst case the reflection will be more than 20 dB down contributing less than 1 dB to the total pressure, and also greater than a wavelength away in distance to insure consistent radiation loading. The loudspeaker should be placed on the ground and tilted such that the transducer axis is aimed directly at the measurement microphone. The microphone's position relative to the source should be exactly the same as for a free-field measurement, were the ground plane not there. The microphone must be placed flush with the ground and at a distance sufficient to be in the far field, usually greater than about three times the maximum extent of the source (the largest dimension), which here includes both the source and image.

The orientation of the loudspeaker source can be varied to investigate various boundary effects [7], and to determine how the baffle and box size affect the radiation pattern [8]. Care must be taken, however, in that the ground-plane technique simulates two sources positioned in mirror image along the measurement axis in free space. The baffle size is hence twice as large and the shape is different than that of a single system alone. While box effects must be studied carefully, other measurements are easily made on the ground plane. Since dispersion is only affected in the vertical direction, polar measurements are easily taken by moving the microphone to various points along the ground plane. Turning the cabinet 90° will allow the other angles of dispersion to be measured along the ground plane as long as a far-field measurement distance is maintained. Distortion and other measurements may be taken just as in any other environment. Where moving a large system or obtaining a large enough measurement distance were once insurmountable problems, all that is required here is moving a few more cars off the parking lot.

In sound reinforcement work, where working with multiple systems in suspended clusters, the ground-plane measurement provides the unique advantage of being able to evaluate the performance of twice as many systems in free space by merely stacking the systems on the ground. Similarly, large line arrays, arc, plane and spherical segments may be synthesized and evaluated with only half as many components.

When evaluating small-size systems or single transducers, current practice has standardized on a 1 metre microphone distance. Since the ground-plane image adds 6 dB to the axial SPL, and doubling the measurement distance in the far-field decreases the SPL by 6 dB, it is convenient to standardize on a nominal 2 metre distance for ground-plane measurements. In this way, with the same power input, a ground-plane measurement at 2 metres will have the same apparent mid and high frequency sensitivity as a half-space or whole-space measurement at 1 metre. At low frequencies, the output will be the same as that in whole-space. In between will be a region where the source directivity increases from omnidirectionality to half-space radiation, determined by total effective baffle size; either that of the source, the source and its image, or the half-space baffle. Above this region, directivity is solely determined by the piston characteristics of the source [9].

EXPERIMENTAL MEASUREMENTS

Figure 3 shows the response of a single 200 mm full range loudspeaker in a 25 litre stuffed, sealed box enclosure, 0.505 m high by 0.355 m wide by 0.215 m deep,

f_{ct} = 60 Hz, Q_{tc} = 0.82. The driver is mounted equidistant from the long sides and 0.2 m from one short side, with the baffle mounted flush in the pit of a 2π ground platform, mic 1 m on driver axis, 2.8 volts input. The response is very smooth through the mid and low frequencies due to the true half-space loading, and the response is 2 dB down at resonance as predicted by the Q of the system.

Figure 4 shows the response of the same system in a 500 Hz anechoic chamber, designed for high frequency work only, 2.8 volts input, mic 1 m on driver axis. While the low frequency limitations of the chamber are quite evident, there is a characteristic rise in the midrange output below 1 kHz due to diffraction effects caused by the enclosure size and shape [8, p. 28]. The high frequency response is substantially unaffected.

Figure 5 shows the response of the same system suspended outdoors 4 1/2 metres above the ground surface, 2.8 volts input, mic 1 m on driver axis. The mid and high frequency response is exactly the same as that in the chamber, and here the total free-field response of the system is intact. The response at low frequencies has only been reduced by a maximum of about 4 1/2 dB from half-space loading rather than the theoretically expected 6 dB, evidently due to an imperfect free-field load for the very long wavelengths below 50 Hz. Had a more open area been available for the measurement environment, true free-field loading could have been maintained to a lower frequency.

Figure 6 shows the system response resting flat on the ground plane with the driver nearest to the ground surface, mic at 1 m distance flush with the ground surface, 2.8 volts input. The low frequency response closely duplicates the suspended free-field curve, but raised 6 dB due to the contribution of the image source.

Figure 7 shows the system ground-plane response with the mic moved to a 2 m distance, 2.8 V input. The 6 dB loss incurred in doubling the measurement distance has cancelled the 6 dB increase due to the image source, and the low frequency response now closely matches the suspended free-field curve. The mid and high frequency response is reduced, however, since the mic is off-axis of the source.

Figure 8 shows the same 2.8 V, 2 m, ground-plane response of Figure 7, but with the system slightly tilted such that the mic is positioned on the driver axis as in the free-field curves. Using this method the agreement is within about 1 dB up to about 13 kHz, corresponding to a wavelength for the extent of separation between the microphone and its image source.

Figure 9 and 10 show the two other possible orientations of object and image source, creating different baffle shapes and source placements, hence different diffraction affects in the 200 Hz to 2 kHz region.

CONCLUSION

The ground-plane measurement technique can be employed to simulate the free-field response of a loudspeaker source, together with its acoustic image. The simplicity of the required measurement environments, together with the relative ease of measurement for large source objects and measurement distances, and the potential for simulating large arrays, makes the method particularly appealing and useful for many general design and evaluation applications.

ACKNOWLEDGEMENTS

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Figure 1. Measurement microphone on axis of measurement object and image source created by the ground plane.

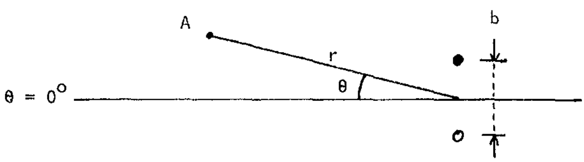

Figure 2. Two equal strength sound sources vibrating in phase located a distance b apart, at distance r and angle θ with respect to point of measurement A. The same conditions apply for a single source located 1/2 b from a rigid boundary.

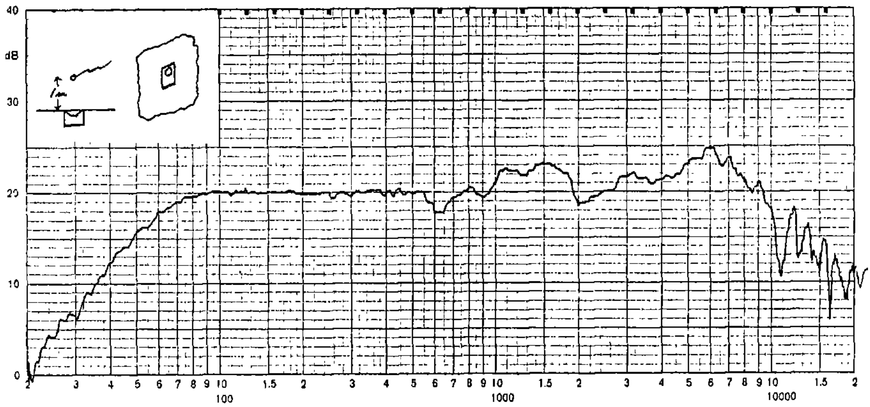

Figure 3. Half space response of a single 200 mm full range loudspeaker in a 25 litre stuffed sealed box enclosure, 0.505 m high by 0.355 m wide by 0.215 m deep, f_{ct} = 60 Hz, Q_{tc} = 0.82, driver mounted equidistant from the long sides and 0.2 m from one short side. Baffle mounted flush in the pit of a 2π ground platform, mic 1 m on driver axis, 2.8 volts input. Measurement range is 40 dB, 70 dB SPL bottom line. Re: 20×10^{-6} N/m^2.

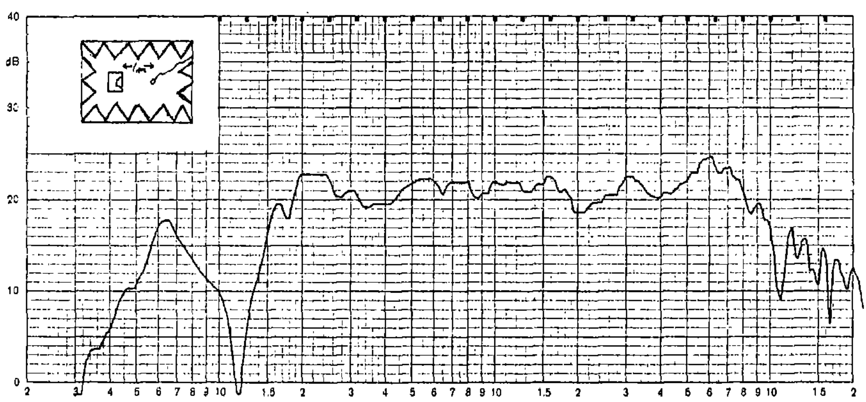

Figure 4. Response of same system in a 500 Hz anechoic chamber. Mic 1 m on driver axis, 2.8 volts input.

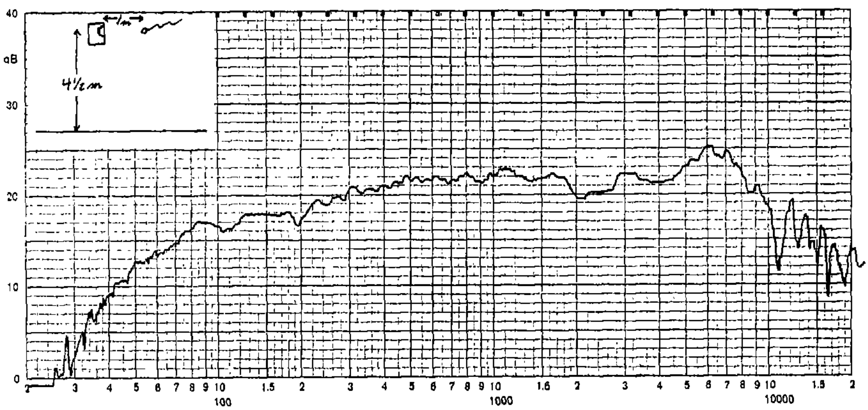

Figure 5. Response of same system suspended outdoors 4 1/2 m above ground surface. Mic 1 m on driver axis, 2.8 volts input.

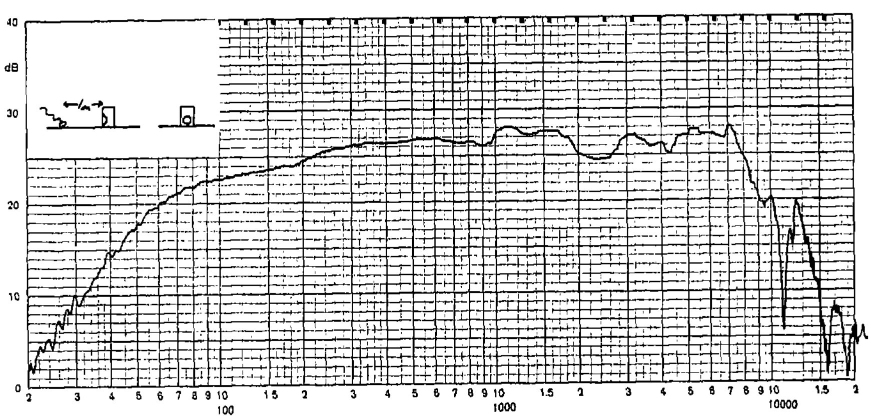

Figure 6. Response of same system resting flat on the ground plane, with the driver nearest the ground surface. Mic flush with the ground at 1 m distance, 2.8 volts input.

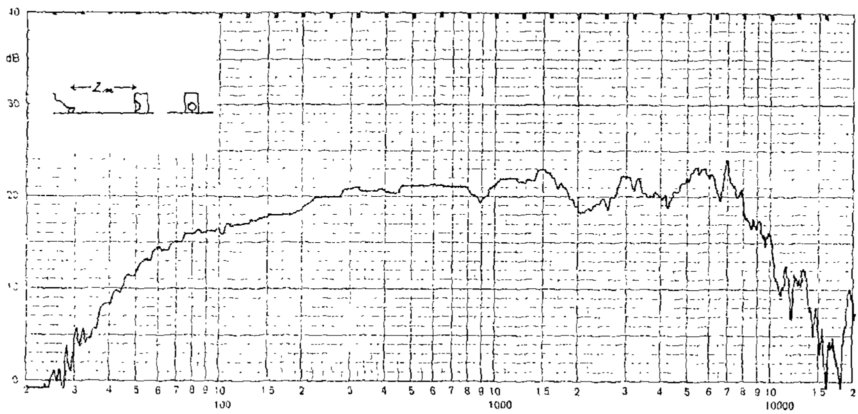

Figure 7. Response of same system on ground plane with mic moved to a 2 m distance, 2.8 volts input.

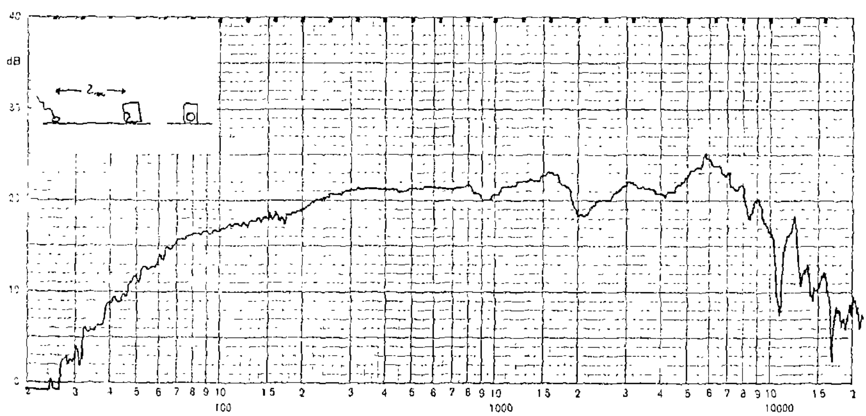

Figure 8. Response of same system on ground plane, but with system slightly tilted so that mic is on driver axis at 2 m distance, 2.8 volts input.

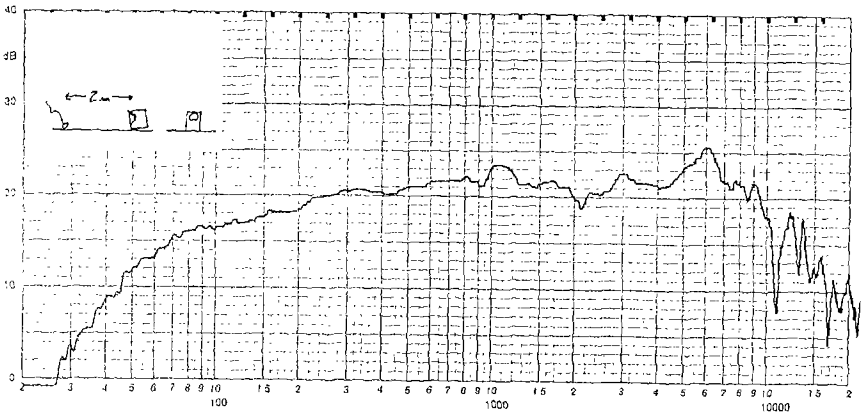

Figure 9. Response of same system on ground plane, but oriented so that the driver is furthest away from ground surface. Tilted so that the mic is on driver axis at 2 m distance, 2.8 volts input.

Figure 10. Response of same system on ground plane, but oriented so that the driver is placed to one side of the baffle. Tilted so that the mic is on driver axis at 2 m distance, 2.8 volts input.