

The Thigpen Waveguide Woofer – A completely new approach to woofer design and worlds first sub woofer that solves room mode problems

The Thigpen Waveguide Woofer is a new type of flat boxless monopole loudspeaker from Bruce Thigpen designed to improve efficiency, material use, weight, size, and solve low frequency room mode problems. The home woofer is so placement friendly, at less than 3 inches thick, multiple panels can be used in any room. The subwoofer version of the speaker technology is designed to be be next to a wall or mounted on the wall, and can be wrapped or painted any color to match room décor.



From the inventor of the Rotary Woofer comes a first principles approach to loudspeaker design, this new woofer alignment addresses room modes which represent the most significant errors at bass frequencies in a listening room.

Summary:

For in room sound reproduction using a loudspeaker, room modes and reflections create the greatest errors in sound system accuracy at the listening position. Below 200Hz, low frequency room modes cause +/-15dB or greater frequency response deviations. Woofer designers overlook this problem and in no other part of the audio chain would we accept these errors. DSP only represents a partial solution and multiple conventional subwoofers are impractical for most domestic living spaces.

The Thigpen Waveguide Woofer is a new loudspeaker and subwoofer configuration that trades enclosure volume for diaphragm area, makes clever use of a moving magnet and moving coil assembly to overcome the reduced air volume in a speaker's enclosure to create multiple tuning frequencies, gains an impedance match with the air using horizontally opposed large surface area diaphragms to increase efficiency, increases low frequency directivity to reduce room modes, does away with the speaker enclosure, and operates apart from Thiele/Small parameters.

This paper will explain how the TWW works and why the loudspeaker industry overlooks 30dB amplitude swings in output from room modes and has been paradoxically steered by software tools derived from Thiele/Small loudspeaker equations that curtail this concept. These room mode frequency response errors are too large for modern DSP which represents a partial solution.

For suggested reading, to really understand transducers, some of the best early books on the science of acoustics and loudspeakers were written by Harry Olson, Leo Beranek, F.V. Hunt, and much later, the Vance Dickason loudspeaker design cookbook, Siegfried Linkwitz's web page, and Don Keele's AES papers, recognized and interspersed below. Room modes were quantified by Manfred R. Schroeder's 1962 article, "*Frequency-Correlation Functions of Frequency Responses in Rooms.*"

How it works:

The Thigpen Waveguide Woofer uses a moving magnet and moving coil horizontally opposed motor structure, a more favorable air mass to diaphragm mass ratio, a large diaphragm area for improved impedance match with the air and half space acoustic radiation using wall loading. The woofer shown above is a very large acoustic source and has the active surface area of more than ten 12 inch woofers.

The mass of the voice coil and magnet are each attached to horizontally opposed diaphragms in a frame to create different tuning frequencies on the front and back surfaces. It can be sealed with very

small amount of air in the enclosed space between the diaphragms. The increase in efficiency is achieved with the large diaphragm area and the much better impedance match with the air offsetting the loss of box volume.

In a traditional loudspeaker, the magnet and loudspeaker basket provide a magnetic field for the voice coil, and their presence adds weight. The Thigpen Waveguide Woofer design uses a magnet for voice coil EMF, but more importantly, the magnet is also used to add mass for tuning the speaker's front and rear diaphragm (cone) surfaces, as a result much less enclosed air volume is needed. As the speaker's cone gets larger, the enclosure volume required becomes (relatively) smaller, all while the "box" remains very thin and light.

Loudspeaker History (abbreviated) -

The moving coil loudspeaker originated in Europe, then improved on in the United States by Rice and Kellogg around 1925, was originally designed using a suspended cone attached to a moving coil and installed on a baffle or in an enclosure. For good low frequency performance loudspeaker enclosures were very large, (sometimes disguised as furniture) which was to prevent the enclosed air from affecting the tuning frequency.

At the time, amplifier power was limited to a few watts. Large horns were utilized to increase the efficiency and output when needed (theaters). For everything from table radios to high fidelity sound systems, these loudspeaker designs were prevalent through the 1950's

Introduced in 1954, Acoustic Research developed Ed Vilchur's "air suspension" loudspeaker which loosened the suspension of the cone and used the air as a spring in a smaller sealed enclosure to create the tuning frequency and control the woofers response. By using the compliance of the air as a spring, this extended the low frequency performance, lowered distortion, and enabled a much smaller loudspeaker enclosure, you had better bass response and a smaller size which made the speaker far more tolerable in the typical household at the expense of efficiency. This invention, combined with more powerful tube and solid state amplifiers entering the market at the same time balanced out the loss in efficiency, enabled more practical stereo audio reproduction and created smaller, attractive, welcomed products.

A number of other audio companies, KLH, Allison, and Advent embraced the air suspension loudspeaker and were very successful.

For a thorough history of the vented loudspeaker, please see "Vented Box Loudspeaker Systems part 1" by Richard Small for a more in depth discussion.

Preceding and along side the acoustic suspension loudspeaker were attempts to increase efficiency by using the rear wave from a moving coil loudspeaker. Bass reflex, vented, and passive radiator equations were published by Richard Small and Neville Thiele that became ubiquitous for loudspeaker design.

From Richard Small:

“The vented-box loudspeaker system is a direct-radiator system using an enclosure which has two apertures. One aperture accommodates a driver. The other, called a vent or port, allows air to move in and out of the enclosure in response to the pressure variations within the enclosure.”

The fundamental idea of a vented enclosure was first described in a patent by Thuras in 1930. While the concept existed, practical applications were limited due to the lack of accurate calculations and design methods.

In the mid-1950s, F. J. van Leeuwen published research that provided a more accurate way to analyze and design vented enclosures, marking a significant step forward in the technology.

Researchers like Neville Thiele and Richard Small further developed the theory behind vented enclosures, utilizing computer modeling to optimize designs and achieve better performance. This research and their AES papers created excellent tools that have guided loudspeaker design which continues to the present day.

While the above created significant improvements in the loudspeakers low frequency performance, they did not look at woofer performance in a room, modes with 30dB amplitude swings are still there, and every domestic room environment yields different results!

It is important to point out that the Thiele/Small equations, or even Hoffmans’s Iron Law do not apply to the Thigpen Waveguide Woofer. Hoffman did not consider acoustic impedance as a variable and the Thiele/Small equations are expressly stated (simplified) to work with loudspeaker cone areas where $ka \ll 1$, meaning the circumference of the cone (or cone area) is typically much shorter than the wavelength of sound.

A speaker cone cannot fully match the impedance of free air, a significant amount of acoustic energy is lost, efficiencies of home speakers hover around 1%.

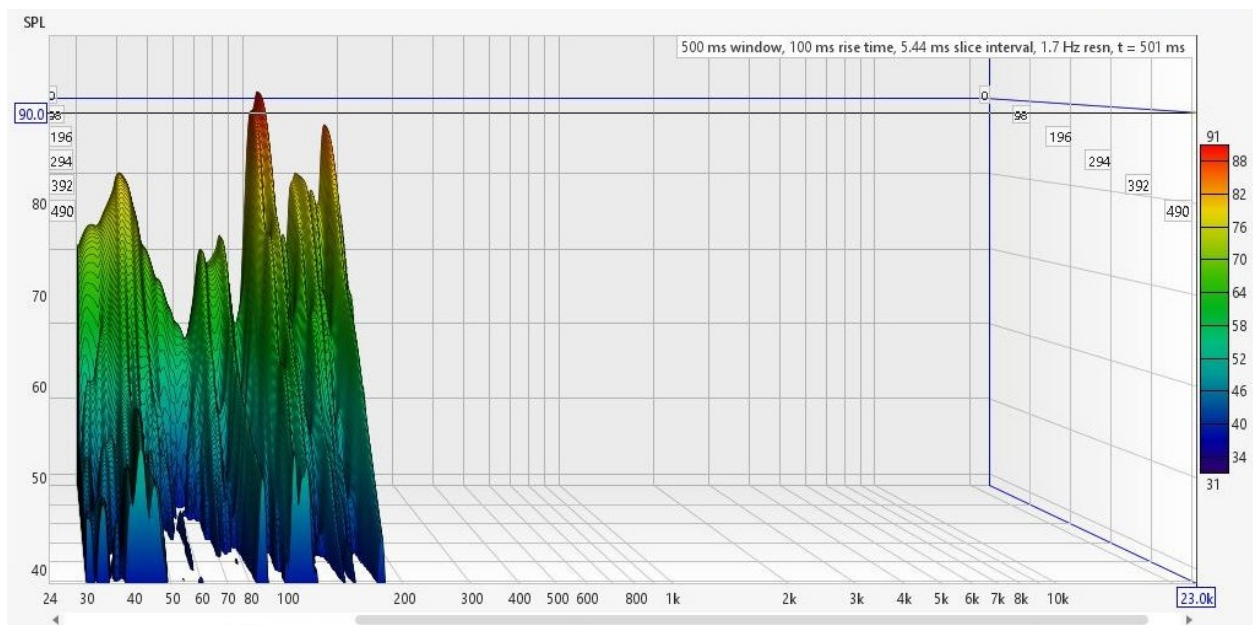
Today, sealed and vented loudspeaker designs are universal, considered to be practical with good performance, widely used in various speaker systems, including home audio, professional sound reinforcement, and subwoofers, due to their ability to produce deep bass frequencies in relatively small enclosures.

Significant Limitations have existed:

Low frequency sound sources designed using direct radiator “cone” loudspeakers require heavy large mostly rectangular enclosures and typically occupy floor space in a home environment.

In domestic room audio sound reproduction, both sealed (2nd order low frequency cutoff) and vented loudspeakers (4th order cutoff) including passive radiators are low frequency point sources that radiate omnidirectionally and create scattered sound pressure vector reflections resulting in room modes and multiple pressure sum and difference phase changes in the frequency response throughout a room.

The “waterfall” shown below is typical of actual woofer response in a domestic living space.

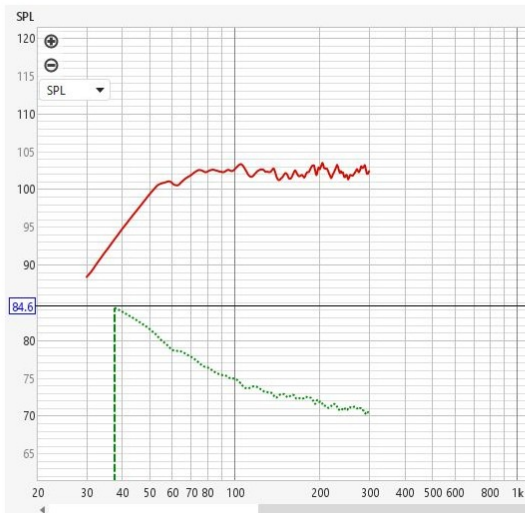


The traditional woofer design approach, with either a vented or sealed enclosures result in very low efficiency. Even a 12 inch woofer is limited to about 2.5% regardless of the motor structure because of a very poor impedance match with the air. (per Don Keele)

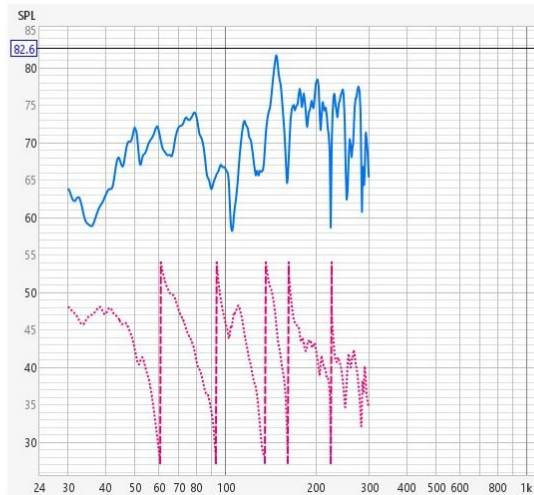
Virtually all home woofers used as part of full range speakers including subwoofers are designed using Thiele/Small parameters. These parameters create technically competent woofers with excellent performance measured up close (anechoically). When you put them in a typical domestic room living space and test them at the listening position with high resolution, the results are poor.

Here is a near field and actual room measurement at the listening position of the same woofer. With more than 20dB of amplitude swings, in no case would these actual room measurements be accepted for any other piece of audio gear.

Nearfield sealed woofer measurement



The same woofer in a typical room



Even used in multiples around a room, they only approximate flat response and just as important, cannot control the decay rate of the low frequency sound radiated into a domestic home living space.

When the nulls are taken into account the real efficiency is considerably lower than the stated anechoic efficiency. A typical consumer product using these woofer designs is on the order of .5-2% efficient.

Digital signal processing can reduce the peaks, but cannot “fix” the dips (sometimes infinite) or room decay times, DSP represents only a partial solution unless you deploy a large number of conventional woofers which is rarely practical.

Very few other endeavors would accept such a low level of efficiency, it is because human hearing is so incredibly sensitive (an extremely loud sound to us does not represent significant sound pressure in the air, about .0002psi) and amplifier power is inexpensive, that this is tolerated.

The industry claims we cannot hear a 30dB (1000:1) or greater swing in low frequency output of a speaker in a room citing hearing acuity studies, very typically room measurements are “smoothed over” in measurement graphs.

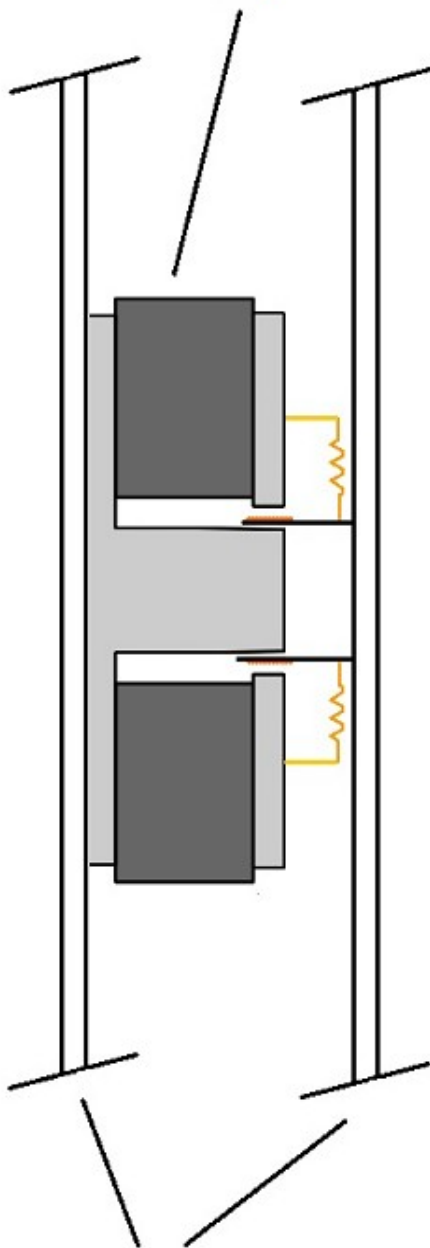
The Thigpen Waveguide woofer:

The Thigpen Waveguide woofer is closest to a horn loudspeaker, noting that the math defining the

mouth area of the horn and acoustic impedance is applicable. This is a new type of loudspeaker where box volume is traded for diaphragm area. It is facilitated with both a moving magnet and moving coil configuration. Diaphragm area is achieved by using parallel horizontally opposed planes (where both sides become the speaker's diaphragm or cone) of a stiff, light weight material. The motor, a voice coil and magnet span between adjacent planes, the voice coil is attached to a front plane and the magnet is attached to a rear plane, the force of the voice coil simultaneously opposes the two planes.

Parallel plane spacing might be a few millimeters to more than 20 centimeters. The area of each diaphragm plane can be a few square centimeters to more than a square meter. A frame border supports the front and rear planes.

Thigpen Waveguide Woofer voice coil and magnet assembly



large diaphragm area
front and rear

The front and rear diaphragms usually have separate tuning frequencies as a result of the difference in mass between a pole piece and magnet attached to the back diaphragm and the voice coil attached to the front diaphragm with different stiffness designed into the diaphragms. Since the majority of the outer surface of the loudspeaker (typically 85%) is made up of a lightweight diaphragm, the speaker ends up being about 1/3 the weight of conventional loudspeakers. There is no loudspeaker basket or speaker enclosure in the traditional sense.

In this loudspeaker you might have 1 or 2 square meters of diaphragm area with only a 20 liter enclosure volume. Since the diaphragm does not need to move as far to create the same sound pressure, the voice coil(s) and magnets tend to be shorter and smaller.

The key concepts to understand are a large diaphragm area, the (absence of) box volume, low and high frequency directivity control, impedance match with the air, tuning frequencies of the front and rear diaphragms, magnet mass, and the support frame. The

result is a light weight, thin, high efficiency loudspeaker.

This “woofer packaging” allows almost complete control of low frequency performance in a room.

High frequency dispersion, where needed is accomplished with distributed mode methods. Low frequency directivity is controlled by the aspect ratio, area of the diaphragm, and proximity to the listener. The output of the Thigpen Waveguide Woofer loudspeaker represents the sum of the front and rear diaphragm motion using the wall as a baffle. Although this loudspeaker does not use the compliance of the air like a passive radiator, when the stiffness of the front and rear diaphragms are arranged to accommodate the difference in mass of the magnet attached to one side and the voice coil attached to the other side, there will be two electrical impedance peaks associated with it's tuning frequencies.

A conventional direct radiator loudspeakers impedance (mis)match with the air is the key to understanding how this loudspeaker works, how you can substantially reduce the box volume, and make other parameters dominant for acceptable performance. The acoustic impedance is similar to that of a horn's loudspeakers mouth area.

Once you have the flat form factor, while not required, it is then much easier to use the listening volume of a room as a low frequency waveguide. another method, because of the size of the diaphragm, moves the woofer acoustically closer to the listener which automatically minimizes room modes at the listening position.

Why it works, but Thiele/Small equations imply that it will not work.

Don Keele's 1991 AES paper describes the theoretical maximum efficiency of a loudspeaker with respect to diaphragm area demonstrating that efficiencies increase with diaphragm area and the loudspeakers surface area also describes (is similar to) the cutoff frequency of a horn loudspeakers mouth area. Graphed Below:

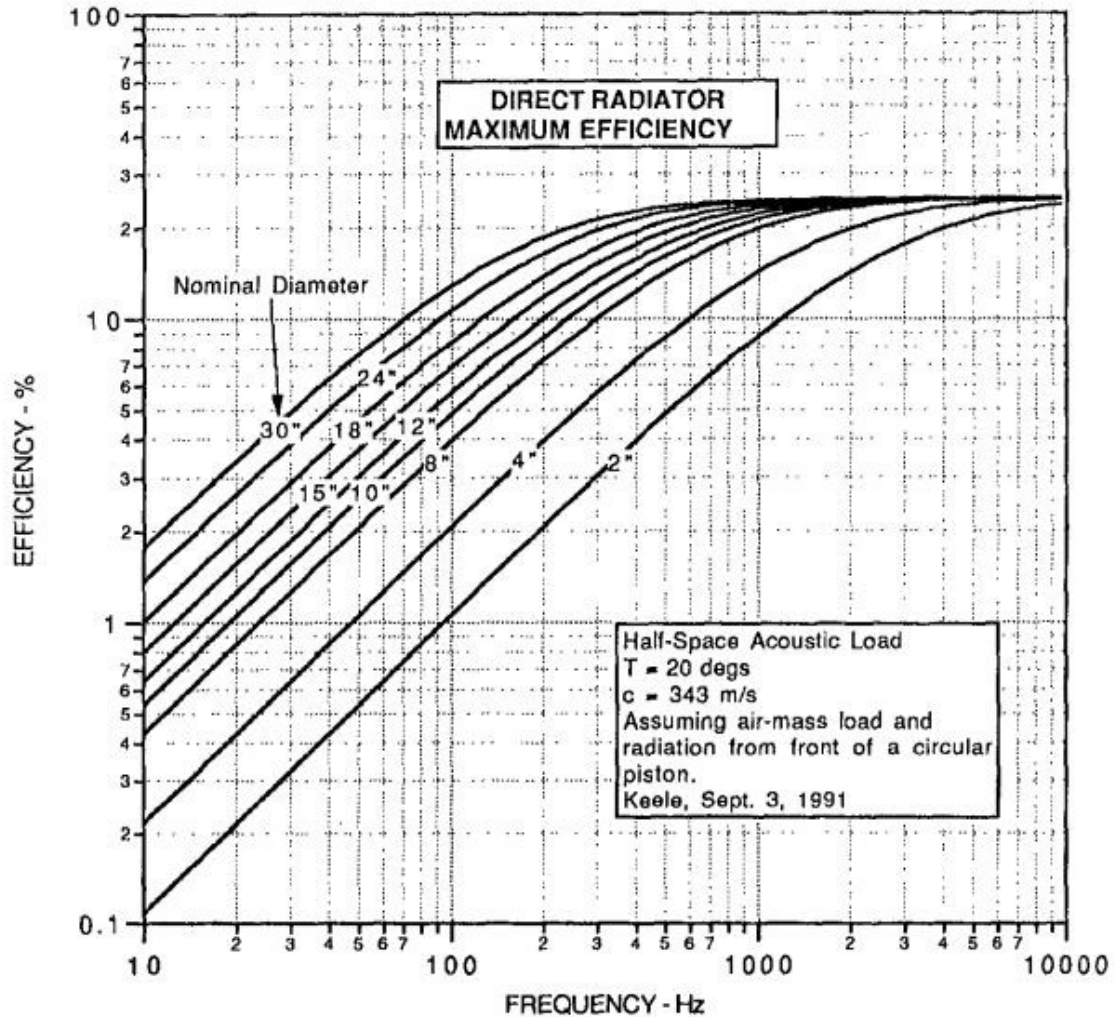
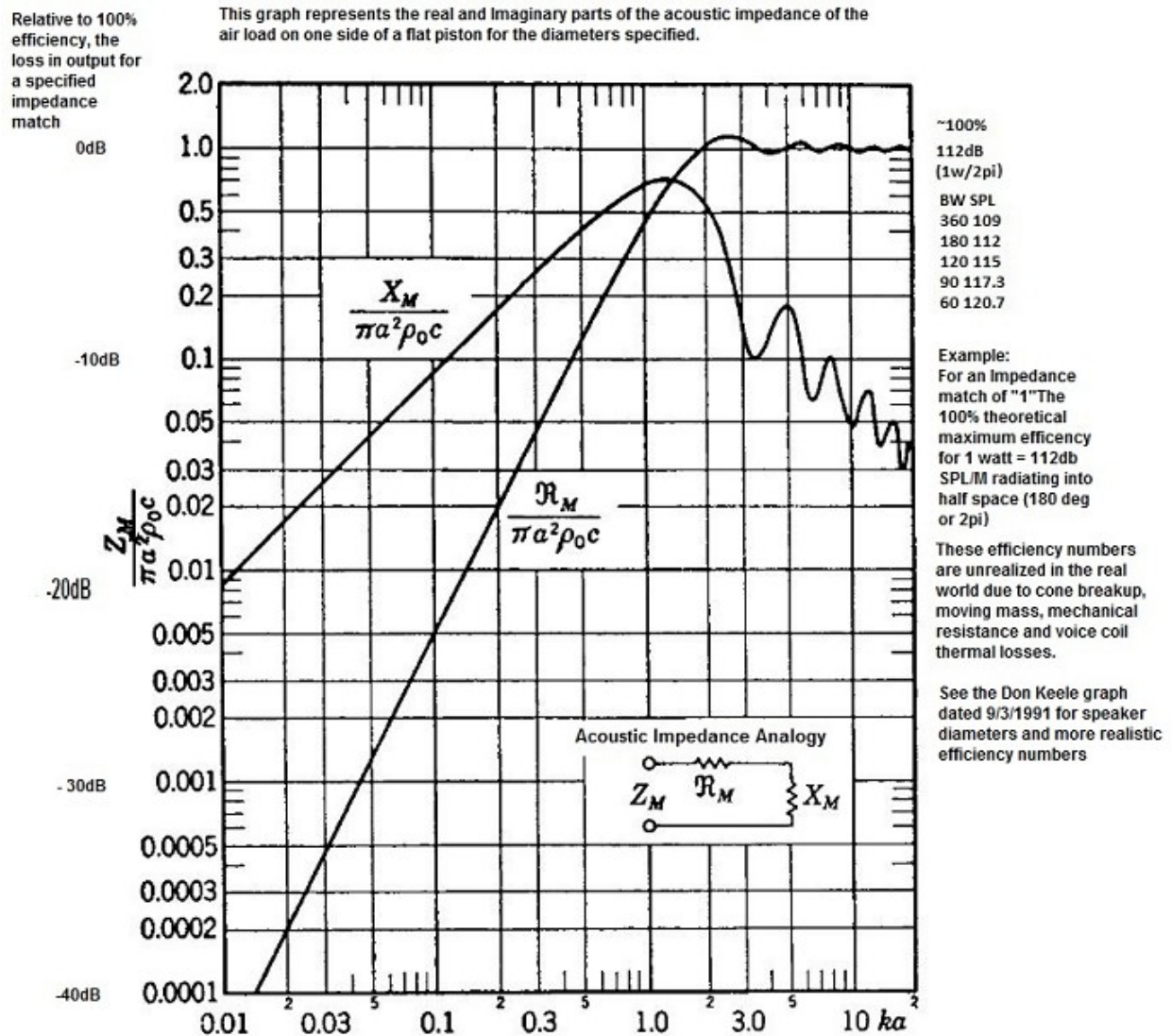


Fig. 11. Theoretical maximum efficiency of a direct-radiator driver vs frequency, for various nominal advertised driver diameters ranging from 2 to 30 in. For example, the graph shows that a 12-in driver can be no more than 2.5% efficient at 40 Hz, no matter how you manipulate its parameters! The graph emphasizes the point that if you want high efficiency at low frequencies you need a large diameter radiator or equivalently an array of smaller diameter radiators having the combined area of the larger radiator.

Below The work of Harry Olson and Leo Beranek discuss the impedance match with a cone and the air: Annotated graph:



For $ka < 0.5$ the air load reactance varies as the first power and the resistance varies as the second power of frequency. For ka greater than about 2 the reactance becomes small compared to the resistance and the resistance approaches a constant value.

Where the radiation impedance is resistive, more power is radiated for a given volume velocity of air

Ideally the radiation impedance is nearly resistive ($ka > 1$) or circumference over the wavelength, $C/\lambda > 1$, exactly the same as the mouth of a horn.

If the speaker behaves like a piston cone velocity doubles for each halving of frequency, output is controlled by the mass of the moving system because of the decreasing radiation resistance, output is the square of the cone velocity times the square of the area (x constants)

For ka greater than 2, the velocity is inversely proportional to frequency

The reactive components of air:

To a loudspeaker, air is capacitive at low frequencies and inductive at high frequencies, (electric circuit analogy) if the capacitor can be made larger by increasing diaphragm area, the cutoff frequency where the velocity of diaphragm motion is decreased transitions to lower frequencies.

Where $KA > 1$, (the loudspeaker cone area is equal to or greater than the wavelength of sound produced) a larger diaphragm improves power transferred to the air and the wave becomes planar rather than spherical which helps to control room modes.

The TWW is designed to operate against a wall with a small gap between its back side and the wall, the wall becomes a large baffle further increasing diaphragm area and efficiency. It takes up almost no floor space and is about as thick as a framed piece of art on a wall.

From Roy Allison (using the wall behind the speaker):

“Reflected energy increases the instantaneous density of the air in front of the woofer at very low frequencies. This provides an improved impedance match, and the efficiency of the woofer is thereby increased, along with the woofer's power output. “

Air Mass Load:

In any loudspeaker the goal is to make the diaphragm as light as possible, the largest gains in efficiency are achieved when the diaphragm mass to air load mass approach 1. While this mass ratio is accomplished in Electrostatic and Planar Magnetic loudspeakers, it is extremely difficult to achieve in direct radiator cone type loudspeakers. However, if you make the loudspeaker diaphragm extremely large, for a given diaphragm mass, counterintuitively, this ratio tends to converge.

From Vance Dickasen's "Loudspeaker Design Cookbook" the equation shows that as the surface area of the diaphragm increases, the air mass driven goes up at a rate raised to the 1.5 power:

8.40 CALCULATING DRIVER AIR-MASS LOAD.

The air has mass and exerts a pressure on the surface of a cone which needs to be accounted for in cone assembly mass measurements. The amount of radiation air mass load depends upon the total surface area of the cone and is calculated by:

$$M_{mr} = 0.575 \times S_d^{1.5}$$

Table 8.3 gives the typical free air radiation mass load for different diameter drivers.⁴

TABLE 8.3

Diameter	S_d (M ²)	Mmr (grams)
18"	0.1300	27.0
15"	0.0890	15.3
12"	0.0530	7.0
10"	0.0330	3.5
8"	0.0220	1.9
6.5"	0.0165	1.2
6"	0.0125	0.8
5.25"	0.0089	0.5
4.5"	0.0055	0.2
3"	0.0038	0.1

From Don Keele's 1991 paper:

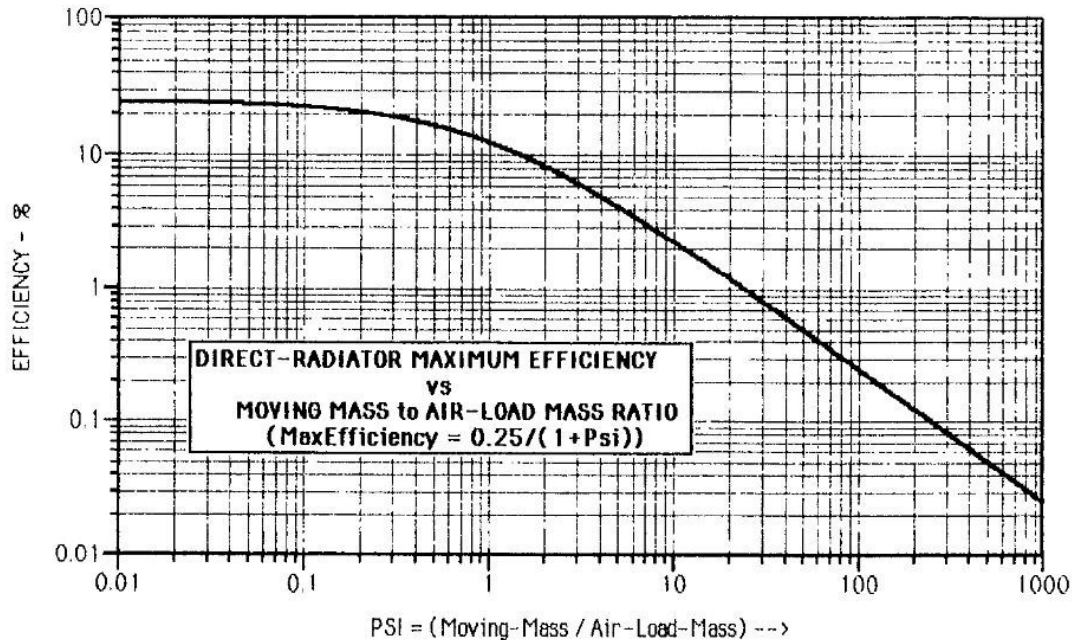


Fig. 14. Plot of direct-radiator maximum efficiency as a function of the moving mass to air-load mass ratio ψ . The plot starts at an efficiency of 25% and then at $\psi = 1$ starts to smoothly decrease 3 dB for each doubling of ψ . Again, this plot emphasizes that high efficiencies are only attained when the moving mass to air-load mass ratio is low ($\psi < 1$)

Using a very large Diaphragm removes the need for a large box:

The Physics of Air Mass Load (Why Thiele Small parameters steer us away from the Thigpen Waveguide Woofer)

The Relevant T/S Parameters

Mechanical Mass M_{ms} : The physical weight of the cone, voice coil, and suspension.

Acoustic Mass M_{as} : The air mass in front of the speaker diaphragm

Because air is incredibly light compared to the speaker cone and the wavelength being produced is very long, when the cone moves, the air "slips around or falls away" from the cone, like trying to push air with your hand. Termed an "impedance mismatch" between the moving cone and air limits the power transfer efficiency of a direct-radiator cone speaker.

Efficiency:

Efficiency (η_0) in the low-frequency passband is fundamentally limited and governed by the ratio of wavelength to cone area and moving mass to air-load mass.

Thiele Small equations force the use of relatively heavy cones which are required for deep, low-frequency bass extension in a small box, which goes all the way back to Edgar Villchur's air suspension woofer invention. However, as mass goes up, the efficiency drops because the voice coil motor requires more force to accelerate the cone.

Lighter cones: give you higher efficiency but will not work in a small enclosure to produce low frequencies.

Calculating air mass in front of a speaker cone:

The calculation relies on three main variables:

- ρ_0 : The density of air (typically 1.18 kg/m^3 at room temperature).
- a : The effective radius of the woofer cone (including half of the flexible surround).
- S_d : The effective surface area of the cone, defined as πa^2 . [Google Sites +1](#)

The formula for the front acoustic radiation mass load is:

$$M_{mr} = \frac{8}{3} \rho_0 a^3$$

Example Calculation (12-inch Subwoofer):

If you have a 12-inch woofer, the effective radiating diameter is usually around 26 cm (radius $a = 0.13 \text{ m}$).

$$M_{mr} = \frac{8}{3} \times 1.18 \times (0.13)^3 \approx 0.0065 \text{ kg (or } \mathbf{6.5 \text{ grams}}) \text{ } \textcircled{\text{e}}$$

If a woofer cone weights 65 grams, this implies a cone mass air load mass ratio of 10:1.

Theiles simplified efficiency equation is: $E = 16 \times 10^{-12} V_b \times K$, where K is between 1 and 4 and depends on the type of enclosure. Note that this **does not** address the air load on the front of the diaphragm and is assumed that the radiated wavelength is much longer than the radius of the cone.

So, we see above that the air mass actually goes with the cube of the area, as the area gets larger, the diaphragm (speaker cone) mass scales linearly 1:1 with area while the air mass goes with the cube of the area, the speaker becomes more efficient and;

The box becomes less important!

NB: If you create a speaker with a very large cone efficiency goes up, then you can make a smaller box, the large cone helps to minimize room modes and the listener is acoustically closer to the larger cone.

Room modes are a function of the wavelength being produced and the dimensions of the room magnified by the omnidirectional radiation of a woofer where the wavelengths are much shorter than the dimensions of the cone.

From Don Keele's 1991 -10 AES paper: "the widely used methods of direct radiator loudspeaker system analysis, based on the pioneering work of Thiele and Small neglect the radiation impedance components in deriving the system response functions and for low frequencies, the maximum available efficiency is proportional to cone area and the maximum efficiency depends only on the moving mass to air load mass ratio."

These assumptions were made to greatly simplify the equations and assumed that the radiated wavelengths are much greater than the circumference of the cone, but indirectly cause room mode problems.

The problems are impedance match with the air and room modes. The impedance mismatch is the cone driving the low impedance air with a high impedance source. That ratio improves at a rate **greater** than the T/S parameters Sd^2 implied in the equations.

Room modes are a function of the wavelength being produced and the dimensions of the room magnified by the omnidirectional radiation of a woofer where the wavelengths are much shorter than the dimensions of the cone.

Mechanical air load on a diaphragm is proportional to $8 \times \text{density} \times \text{area}^3$

Don Keeles simplified derived speaker efficiency equation;

$$\eta_{\max} = \frac{2\rho_0 a^3}{3M_{MD}} \quad (50)$$

In a typical driver or array of drivers, the moving mass usually increases in direct proportion to cone area or radius squared (a^2), but the air load mass increases in direct proportion to radius cubed (a^3), which makes the maximum efficiency rise in direct proportion to the driver's radius (or linear dimension). This means that as the driver size increases or as the number of like speakers in an array increases, the maximum possible efficiency also increases.

This behavior can be contrasted with the Thiele/Small reference efficiency equation (reproduced here later as Eq. (54)), where the efficiency increases in direct proportion to the fourth power of the radius (a^4 or area squared), and decreases in direct proportion to moving mass squared (a^4 again). This predicts that efficiency is essentially independent of cone size.

Neville Thiele expressly states (Loudspeakers in vented boxes - part 1) that his equations are intended to be used with speaker cones where the circumference of the cone is much smaller than the

wavelength of sound, radiation resistance or air load can be neglected.

The most important part, How to achieve flat bass response in a domestic listening room:

A conventional direct radiator loudspeaker woofer designed using Thiele/Small parameters provides excellent near field performance.

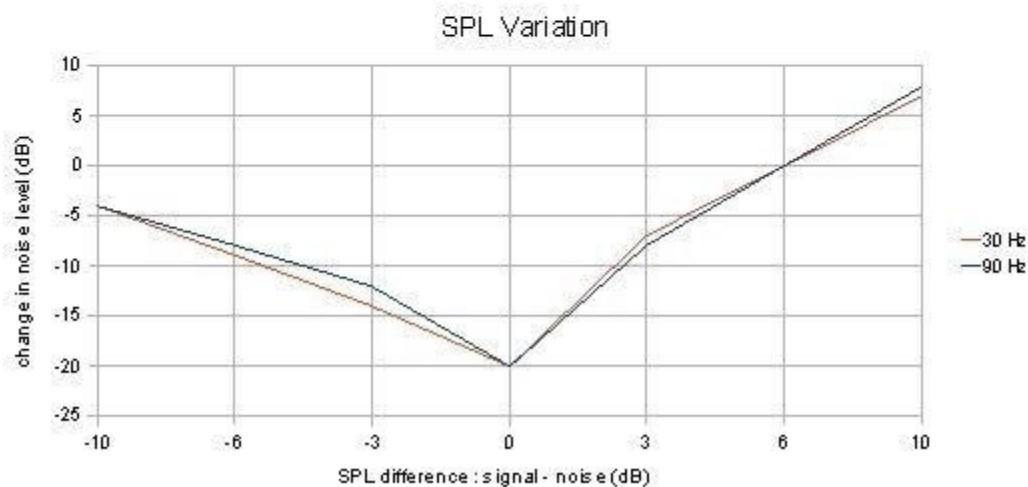
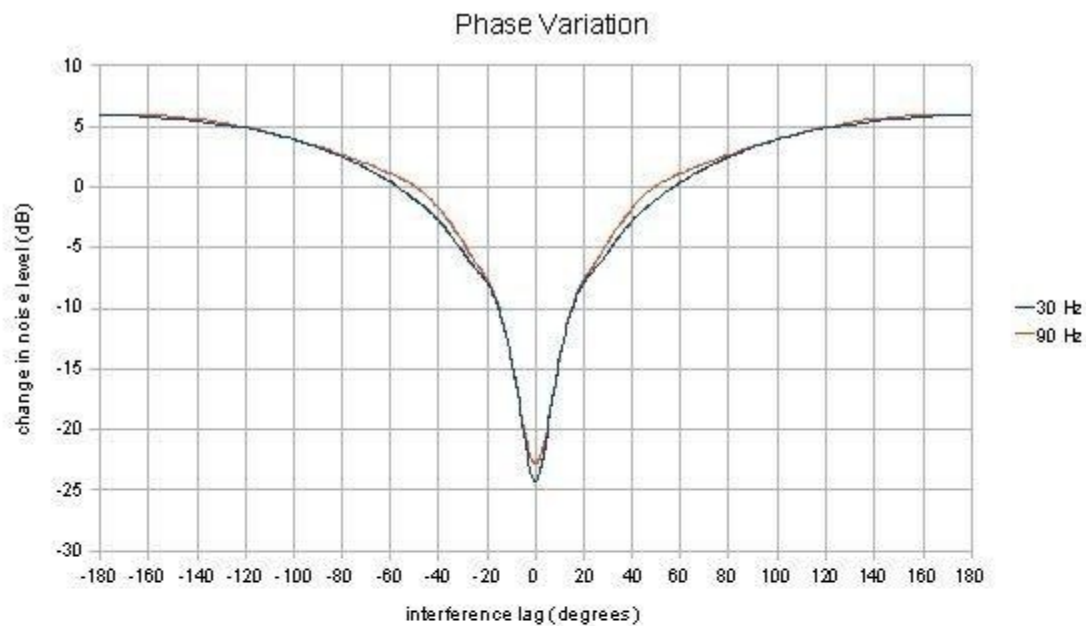
However, in any domestic living space, this is far from ideal.

Conventional home loudspeakers or subwoofers radiate sound hemispherically, placed near side or rear walls create reflections, these long wavelength low frequency reflections, depending on frequency, sum with the source either in or out of phase and cause numerous peaks and dips in the frequency response experienced by the listener. While peaks can be corrected with DSP, severe dips, which can be infinite, cannot be corrected. It should be noted that any correction, creates a loss in real efficiency

Sum and difference phase charts:

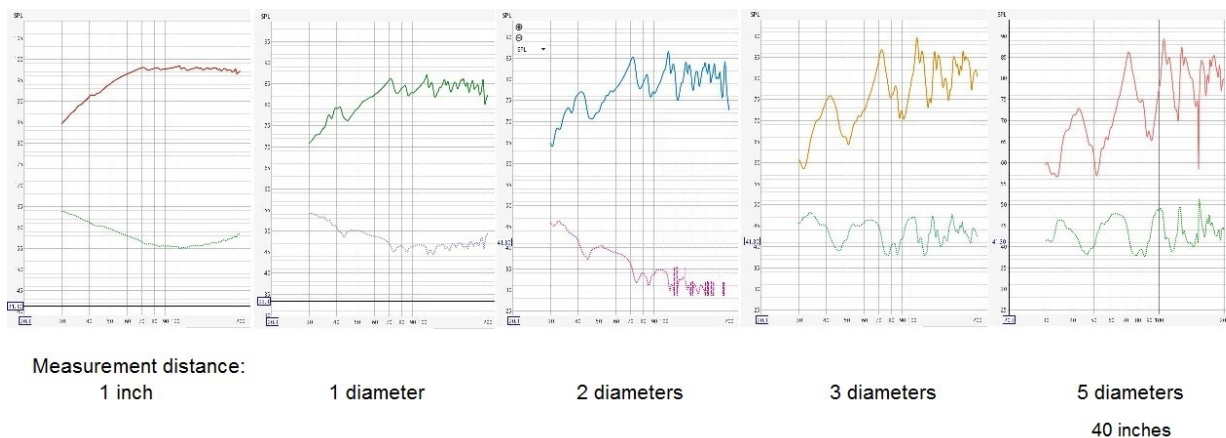
To demonstrate what happens when an omnidirectional low frequency source is placed in a room (below are actual measured results).

This test measures both phase and amplitude changes to show a loudspeakers frequency response changes due to wall reflections from a woofer or subwoofer in a domestic living space. The reflections either add or subtract depending on the amplitude and phase relationships and explain why we see so many peaks and dips in a frequency response below 300hz at the listening position in the rooms modal region defined by Schroeder.



For this paper we are using Theile/Small parameters to design a sealed enclosure for an 8” woofer to document near and far field low frequency measurements as a baseline. Taking the above phase and cancellation results into account, we place the woofer in a domestic living space of approximately 25 x 15 x 8 feet.

Here are the (surprising) measurement results as you move away from the source:



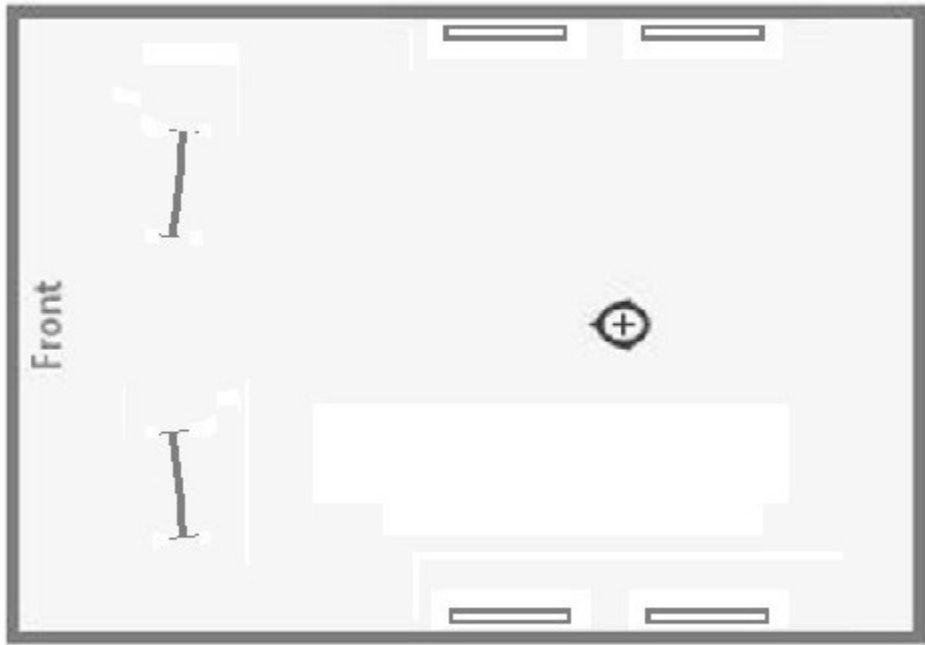
The above results suggest that you need to be relatively close to the low frequency source, OR the low frequency source needs to be much larger to achieve flat low frequency response at the listening position.

Method 1

From Nils Ollerer “Variants of the Double Bass Array”:

“If you can increase the directivity of the low frequency source, you can both increase the radiated power in the room and at the same time decrease the room modes by reducing the reflected energy from the walls. “

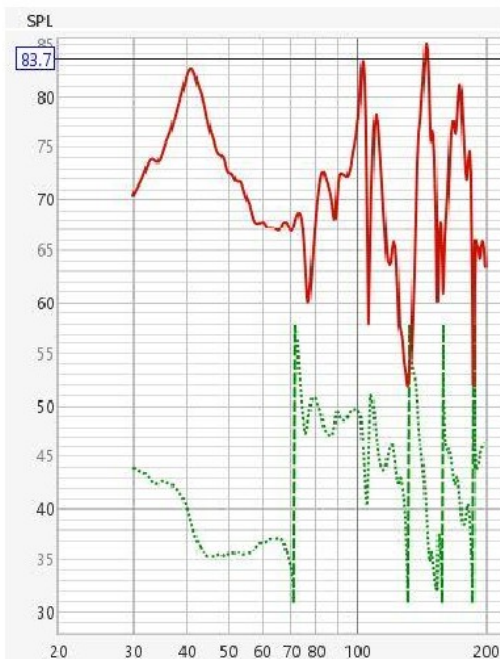
Since the Thigpen Waveguide Woofer’s form factor allows woofer placement anywhere in the room, the above strategy can be easily implemented to gain better control over room modes and obtain much flatter frequency, phase and impulse response at the listening position.



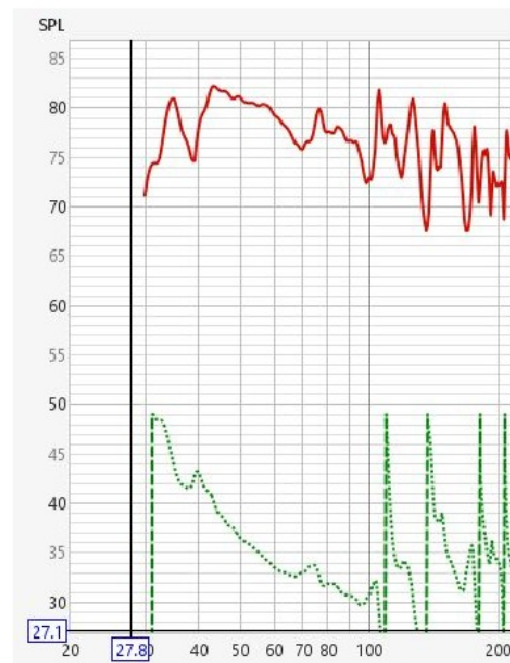
Below are actual results, we go from +/-17dB to +/- 6.5 dB:

Measured at the listening position in a 15 x 25 foot room

Conventional Woofer



Thigpen Waveguide Woofer



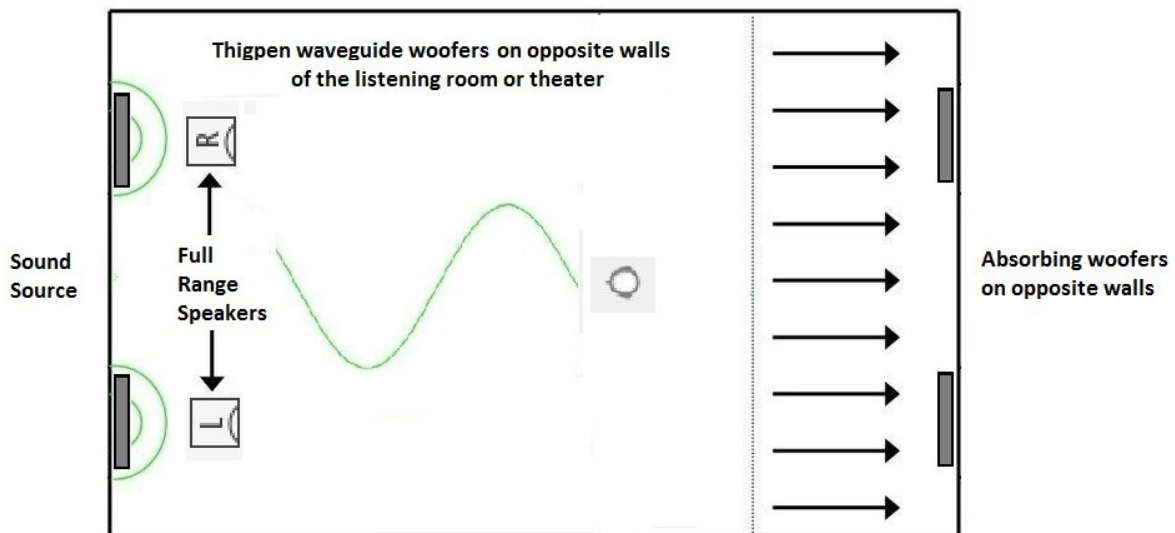
Method 2

Siegfried Linkwitz:

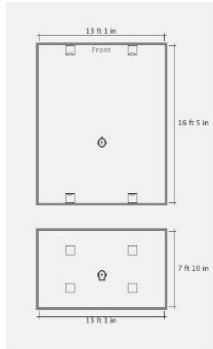
“The ideal listening room acts like a waveguide with the loudspeakers at some distance from the diffuse (live) end of the room and sound traveling past the listener to the open (dead, absorptive) end of the room (see the drawing below). Sound reflections from the wall behind the listener should be attenuated as much as possible, particularly below 200 Hz.”

The Thigpen Waveguide Woofer is the only practical way to implement a double bass array in most listening rooms.

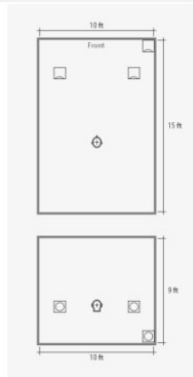
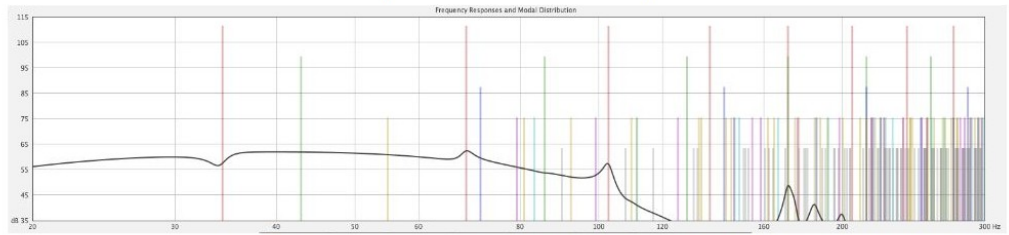
Called “the double bass array” it creates a low frequency plane wave that is projected down the length of the room and absorbed by a complementary pair of woofers operating out of phase, delayed by transit time, and with a slightly reduced level at the opposite end of the listening room.



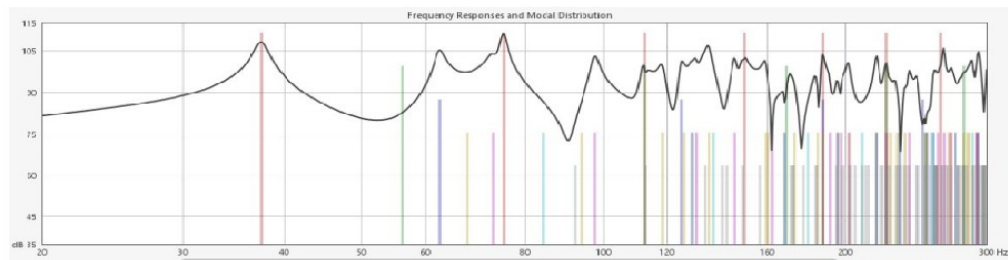
Room EQ Wizard comparison



Waveguide or Double Bass Array



Conventional home stereo with subwoofer



Summary:

The Thigpen Waveguide Woofer is a new loudspeaker and subwoofer configuration that trades enclosure volume for diaphragm area, uses the mass of a loudspeakers voice coil/magnet assembly to overcome the reduced air volume in a speaker’s enclosure to create tuning frequencies, gains an impedance match with the air using horizontally opposed large surface area diaphragms to increase efficiency, increases low frequency directivity to reduce room modes, does away with the speaker enclosure, and operates apart from Thiele/Small parameters.

Two U.S. granted utility patents are: US 10951966 and US 11546680



Research credits and suggested reading on the subject of Loudspeakers:

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