The Thigpen Waveguide Woofer – The worlds first flat subwoofer

The Thigpen Waveguide Woofer is a new type of boxless monopole loudspeaker from Bruce Thigpen that improves efficiency, material use, weight, and size when compared to a traditional loudspeakers. The home woofer is only 3 inches thick. The subwoofer version of the speaker technology is designed to be be next to a wall or mounted on the wall, and can be painted any color.

A counter intuitive approach to loudspeaker design:

It 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 prototype shown above has the active surface area of about eight 12 inch woofers.

The mass of the voice coil and magnet are each attached to horizontally opposed diaphragms in a border frame to create different tuning frequencies on each side. It can be sealed with very small amount of air in the enclosed space between the diaphragms. The increase in efficiency is achieved with a larger diaphragm area and the much better impedance match with the air offsetting the loss of box volume.

In a traditional loudspeaker, the mass of the magnet and loudspeaker basket provide EMF 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 speakers front and rear diaphragm (cone) surfaces, as a result much less enclosure volume is needed. As the speaker's cone gets larger, the enclosure volume required becomes (relatively) smaller, all while the box is very thin and light.

This paper will explain how the TWW works and why the loudspeaker industry has been paradoxically steered by software tools derived from Thiele/Small loudspeaker equations that curtail this concept.

For suggested reading, 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 web page, and Don Keele's AES papers are recognized and interspersed below.

Loudspeaker History (abbreviated) -

The moving coil loudspeaker originated in Europe, then improved on by Rice and Kellog around 1925, was originally designed using the stiffness of the cone and suspension 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 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. 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 a much more attractive and very successful products.

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

For a more thorough history of the vented loudspeaker (Please see “Vented Box Loudspeaker Systems part 1” by Richard Small for a more in depth discussion) 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 have guided loudspeaker design which continues to the present day.

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

Today, sealed and vented loudspeaker designs are ubiquitous, 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.

The limitations.

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 (2^{nd} order low frequency cutoff) and vented loudspeakers (4^{th} 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 sums and differences in the frequency response throughout a 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 sound radiated into a domestic home sized room.

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 1-2% efficient.

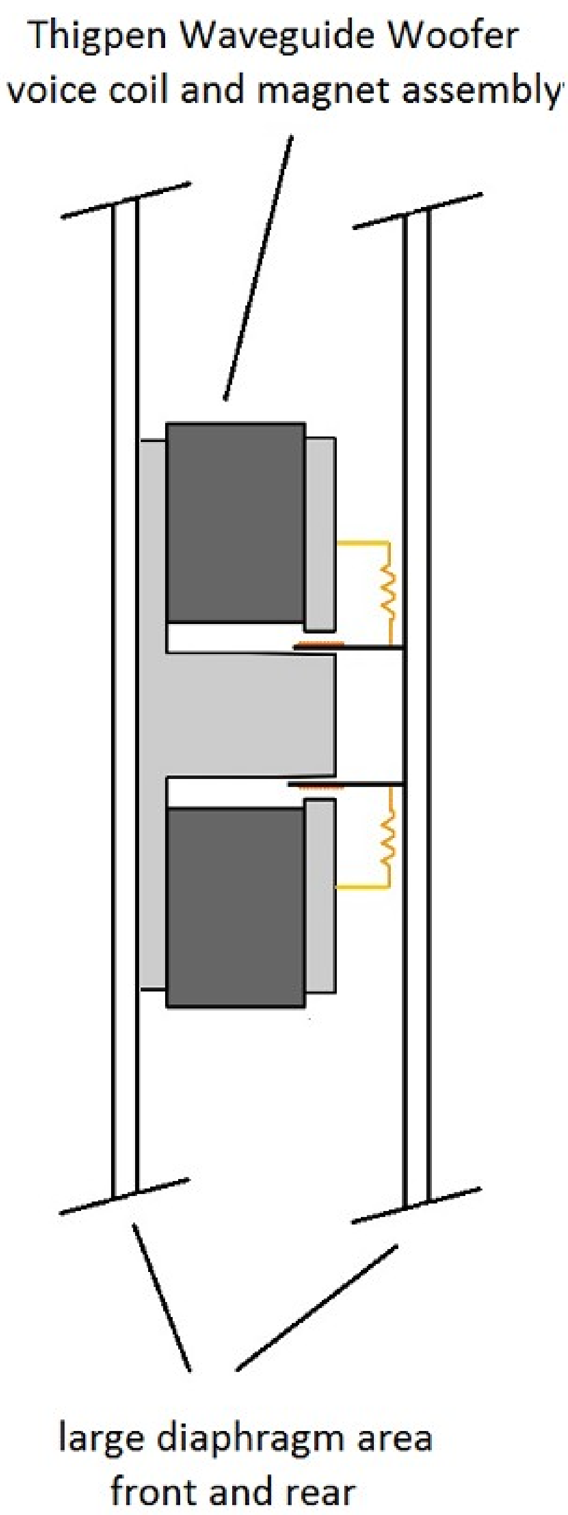
Very few other endeavors would accept such a low level of efficiency, it is because human hearing is so incredibly sensitive (a loud sound to us does not represent a lot of sound presssure in the air, about .0002psi) and amplifier power is inexpensive, that this is tolerated.

The Thigpen Waveguide woofer:

The waveguide woofer is closest to a horn loudspeaker, noting that the math defining the mouth of the horn and acoustic impedance is relevant. It is a new type of loudspeaker where box volume is traded for diaphragm area. This is facilitated with both a moving magnet and moving coil configuration. Diaphragm area is achieved by using parallel horizontally opposed planes (which become the speakers 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.

The front and rear diaphragms usually have separate tuning frequencies as a result of the difference in mass between the 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 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 a traditional sense.



In this loudspeaker you might have a 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, higher 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. Although this loudspeaker does not operate 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 impedance peaks associated with it's tuning frequency.

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 much easier to use the listening volume of a room as a low frequency waveguide.

Don Keele's 1991 paper describes the theoretical efficiency of a loudspeaker with respect to diaphragm area. Note that efficiences can be much greater than sealed or vented enclosures and the loudspeakers surface area also describes (is the same as) the cutoff frequency of a horn loudspeakers mouth area.

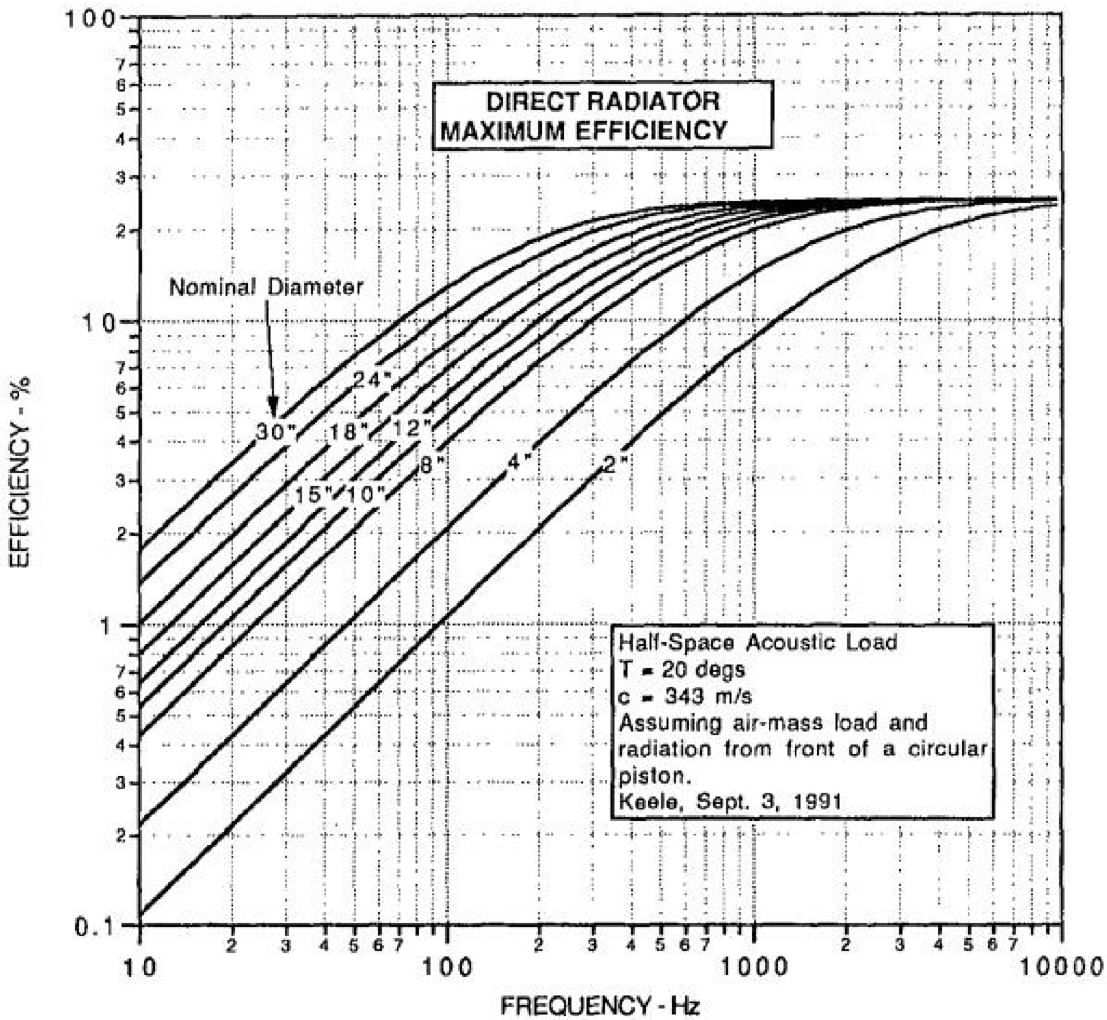
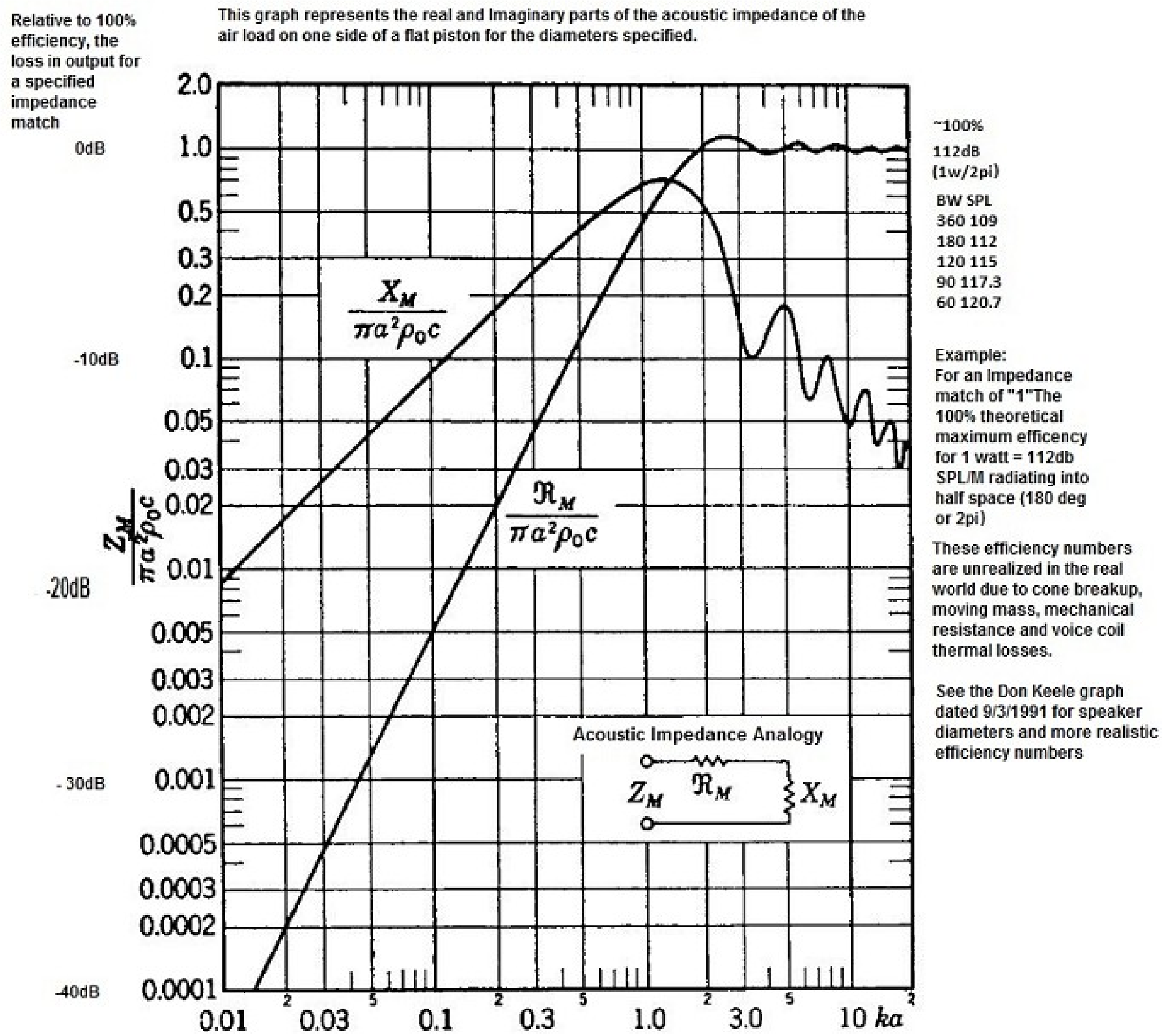


Fig. 11. Theoretical maximum efficiency of a direct-radiator driver vs frequency, for various nominal advertised driver diameters ranging from 2 to 30 in. For example, the graph shows that a 12-in driver can be no more than 2.5% efficient at 40 Hz, no matter how you manipulate its parameters! The graph 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.

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



For ka<.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 circumfernece 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 in 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 large enough by increasing diaphragm area, the cutoff frequency where the velocity of diaphragm motion can reduced to low frequencies.

Where KA>1, the larger diaphragm improves power transferred to the air and the wave becomes planar rather than spherical and this helps to control room modes

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

From Roy Allison:

"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. "

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, 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:

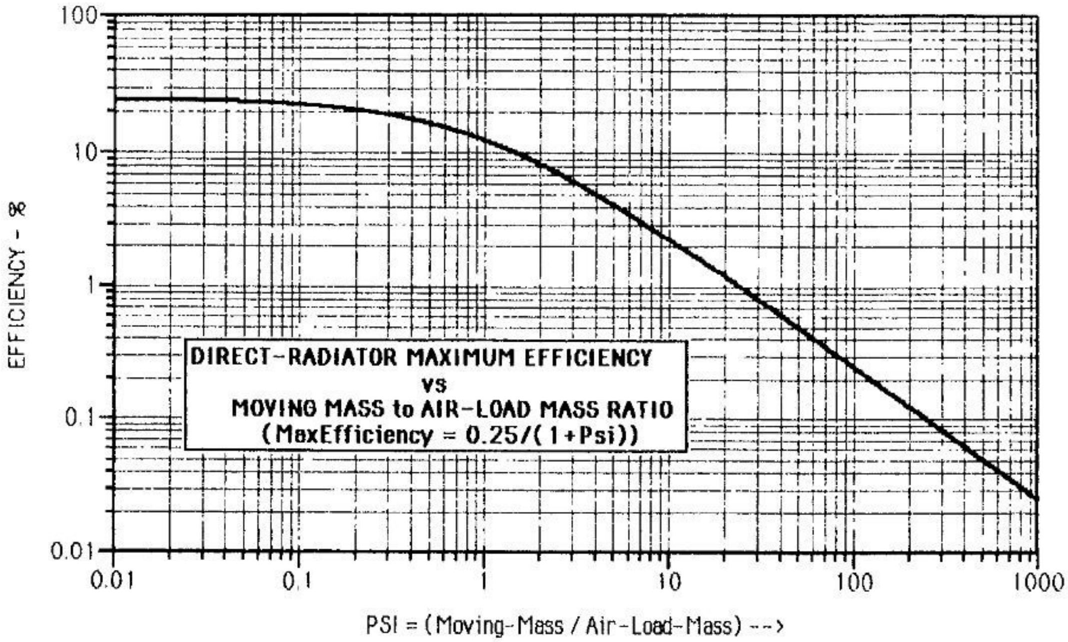


Fig. 14. Plot of direct-radiator maximum efficiency as a function of the moving mass to air-load mass ratio ψ. The plot starts at an efficiency of 25% and then at $\psi = 1$ starts to smoothly decrease 3 dB for each doubling of ψ. Again, this plot emphasizes that high efficiencies are only attained when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

The listening Room:

Siegfreid Linkwitz:

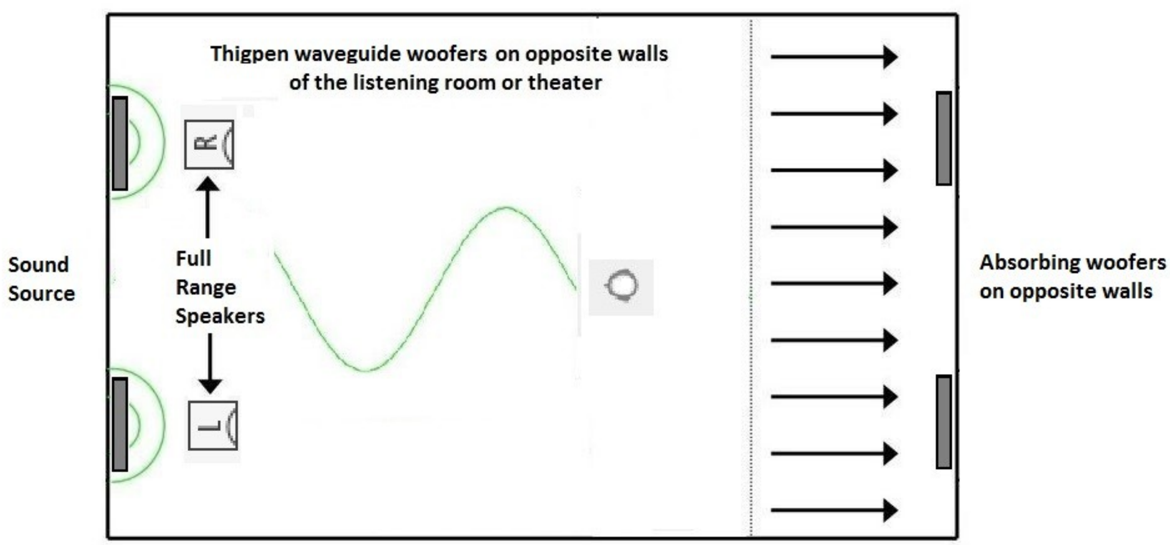
“The ideal listening room acts like a waveguide with the loudspeakers at some distance from the diffuse (live) end of the room and sound traveling past the listener to the open (dead, absorptive) end of the room (see the drawing below). Sound reflections from the wall behind the listener should be attenuated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

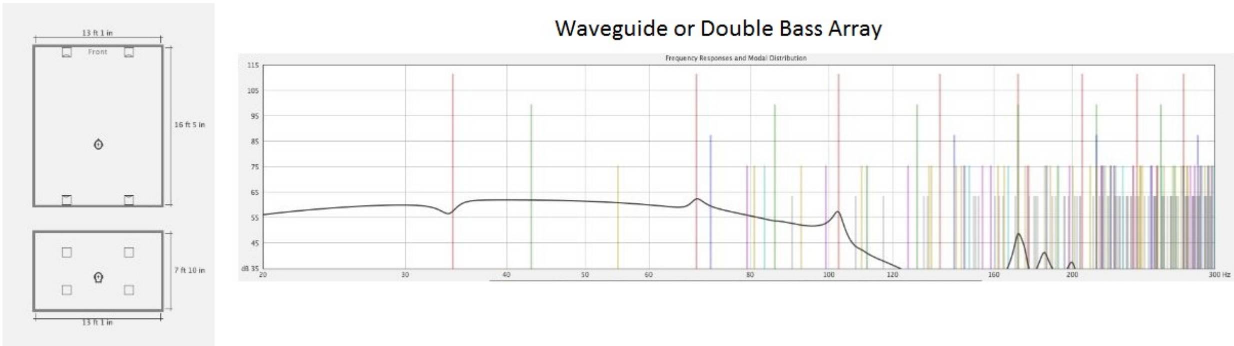
The double bass array creates a low frequency plane wave that is projected down the length of the room and absorbed by a complementary pair of woofers operating out of phase, delayed, and with a slightly reduced level at the opposite ends of the listening room.

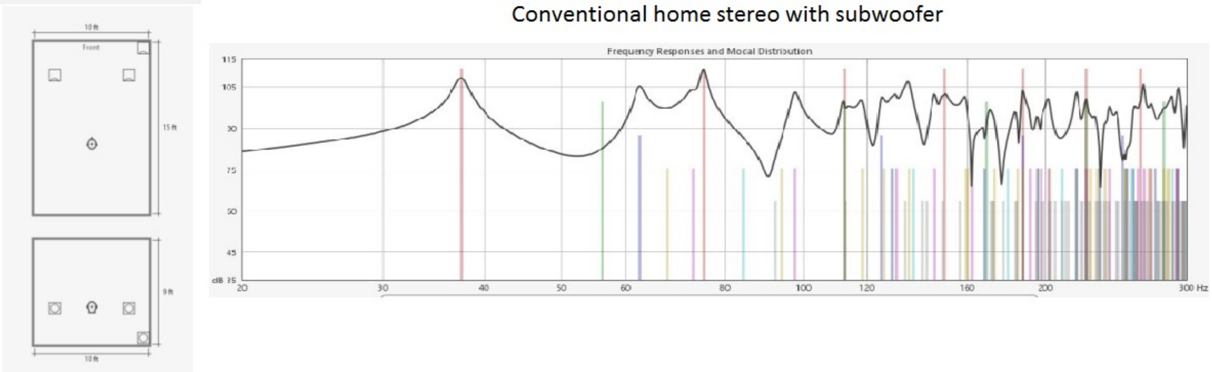
From Nils Ollerer “Variants of the Double Bass Array”:

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. From the REW simulator which does not account for low frequency directivity:



Room EQ Wizard comparison





Summary:

The Thigpen Waveguide Woofer is a new loudspeaker 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 the enclosure and 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 low frequency room modes, and does away with the speaker enclosure.

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

Research credits and For more reading on the subject of Loudspeakers:

Acoustics - Leo Beranek 1954 edition MIT copyright 1954 AES

Frank Massa - AIP handbook Dynamics Corportation of America

Brian Andreron – Understanding radiation impedance - 8/2020, Meetings on Acoustics

Hoffmans Iron law – Audio Magazine March 1971 - Henry Kloss "Loudspeaker Design"

Martin King – Derivation of the acoustic impedance at the mouth of a horn, 7/2017 Copyright 2008

R.H. Small - Efficiency of Direct Radiator Loudspeaker systems – JAES Vol 19 #10 11 1971

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D.B. Keele – Efficiency Comparison horns vs direct radiator – AES preprint #1127 5 1976

D.B. Keele – AES papers are all published online - https://www.xlrtechs.com/dbkeele.com/papers.htm

F.V. Hunt – Electroacoustics – The Analysis of Transduction and it's Historical Background -Acoustical Society of America (1954)

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J F Novak – Enclosures for Low resonance high Performance Loudspeakers – IRE trans audio 1 1959

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Nils Ollerer - "Variants of the Double Bass Array" 2015-2025

Audio Express – simulation techniques: Double Bass Arrays - 11 2024

Audio Science Review – Sam Adams REW simulation of double bass array – 10 2022