

SHIVA WHITE PAPER

A technical paper related to the Shiva subwoofer



REVISIONS

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1 General Description

1.1 What Is Shiva?

Shiva is a new 12" subwoofer driver from Avatar Audio. It features an extremely long Xmax, high power handling, and parameters suited for use in a variety of enclosures. It is designed to give low-distortion, high-SPL bass down to infrasonic frequencies in modest-sized enclosures.

1.2 Physical Dimensions

1.2.1 Mechanical Drawing

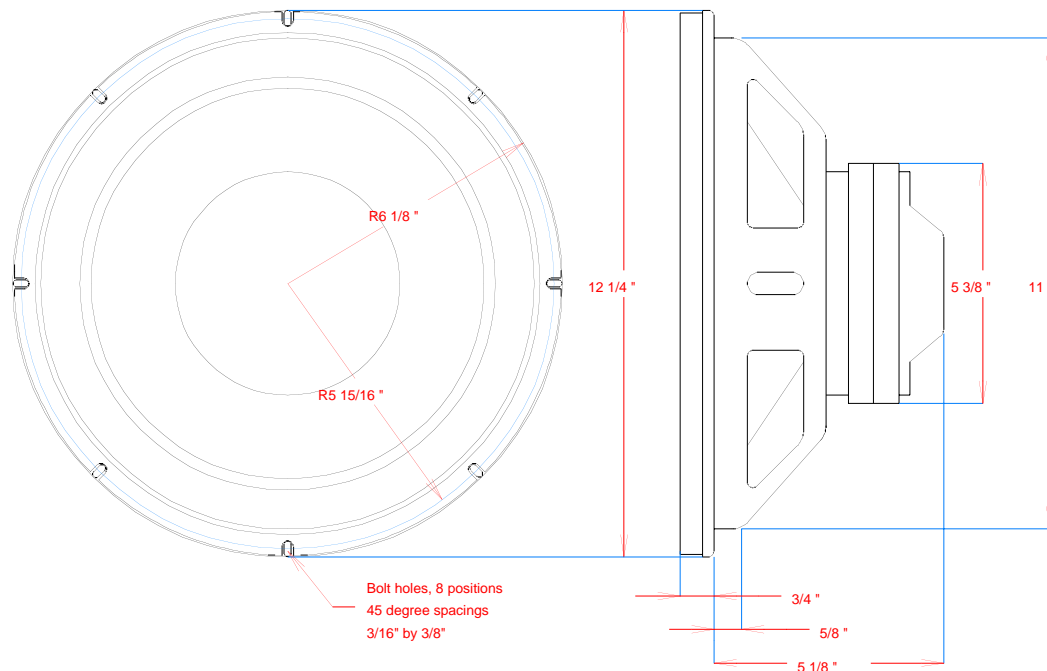


Figure 1 - Shiva Physical Dimensions

Shiva measures 12.25" (31.1 cm) in diameter. It requires a cutout of 11" (28 cm). It has a front-mount height of 3/4" (1.9 cm). It has a front-mount rear-depth of 5.125" (13 cm). There are 8 bolt-holes oriented at 45° increments around the driver. These holes are oval in shape, with a width of 3/16" (4.75 mm) and a length of 3/8" (9.5 mm).

1.2.2 Driver Displacement

For enclosure calculations, Shiva displaces 3 liters (183 cubic inches).

1.3 Thiele Small Parameters

Thiele-Small parameters were defined by A. N. Thiele and R. H. Small. These parameters describe the small-signal behavior of a dynamic (moving cone) driver, and can be used to design and predict the small-signal response of the driver in a multitude of enclosures.

The T/S parameters of the Shiva driver are specified in the first three columns, with independent measurements by DLC Design in the fourth column confirming that these specifications were met:

Parameter	Parallel Connected Voice Coils	Series Connected Voice Coils	Single Voice Coil (other shorted)	DUMAX Test Results (Parallel)
Fs	22 Hz	22 Hz	22 Hz	21.61 Hz
Qts	.39	.39	0.39	0.376
Vas	144 liters	144 liters	144 liters	136.6 liters
Re	2.82 Ω	11.28 Ω	5.64 Ω	2.85 Ω
Le	2.1 mH	8.4 mH	4.2 mH	N/A
Znom	4 Ω	16 Ω	8 Ω	4 Ω
Qes	0.40	0.40	0.80	0.3996
Qms	10.72	10.72	0.76*	6.5
Mms	118.3 grams	118.3 grams	118.3 grams	118.3 grams
Cms	0.44 mm/N	0.44 mm/N	0.50mm/N	0.47mm/N
Rms	1.54 N*s/m	1.54 N*s/m	21.63 N*s/m	2.48 N*s/m
Sd	481 cm ²	481 cm ²	481 cm ²	481 cm ²
BL	10.7 N/A	21.3 N/A	10.8 N/A	10.9 N/A
EBP	55	55	27.5	54
No	0.37%	0.37%	0.20%	N/A
SPL	87.7 dB@1W,1m 90.7 dB@2.83 Vrms	87.7 dB@1W,1m 84.7 dB@2.83 Vrms	84.7 dB@1W,1m 84.7 dB@2.83 Vrms	87.2 dB@1W,1m 90.2 dB@2.83 Vrms
Xmax	±15.1mm	±15.1mm	±15.1mm	±14.9mm Xmax [†] ±21.8mm Xsus [‡]
Pmax	350W/coil; 600W total	600W total	350W total	N/A

Table 1- T/S parameters

* This change in Qms indicates the effectiveness of electromechanical braking caused by the shorted second coil.

† Xmax as defined by the minimum throw to one side of center where the BL product drops by 3 dB. Total linear throw is 29.8mm.

‡ Xsus as defined by the suspension restoring force increasing beyond four times its center value. Total linear throw is 43.6mm.

Of particular interest with the DUMAX test results is the Xmax (maximum linear excursion) and Xsus (maximum physical excursion). Both these numbers are extremely high for any sized subwoofer; in fact, Shiva has greater verified linear travel than any commercial home audio 12" or 15" subwoofer currently on the market.

1.4 Frequency Response

The Shiva frequency response was measured in a $Q=0.6$ (88.5 liter) enclosure. Frequency response was measured in the near-field, in absolute SPL. Drive level was $4V_{RMS}$ (4W delivered to a nominal 4Ω load) for a nominal 93.7 dB SPL level. The measured frequency response is:

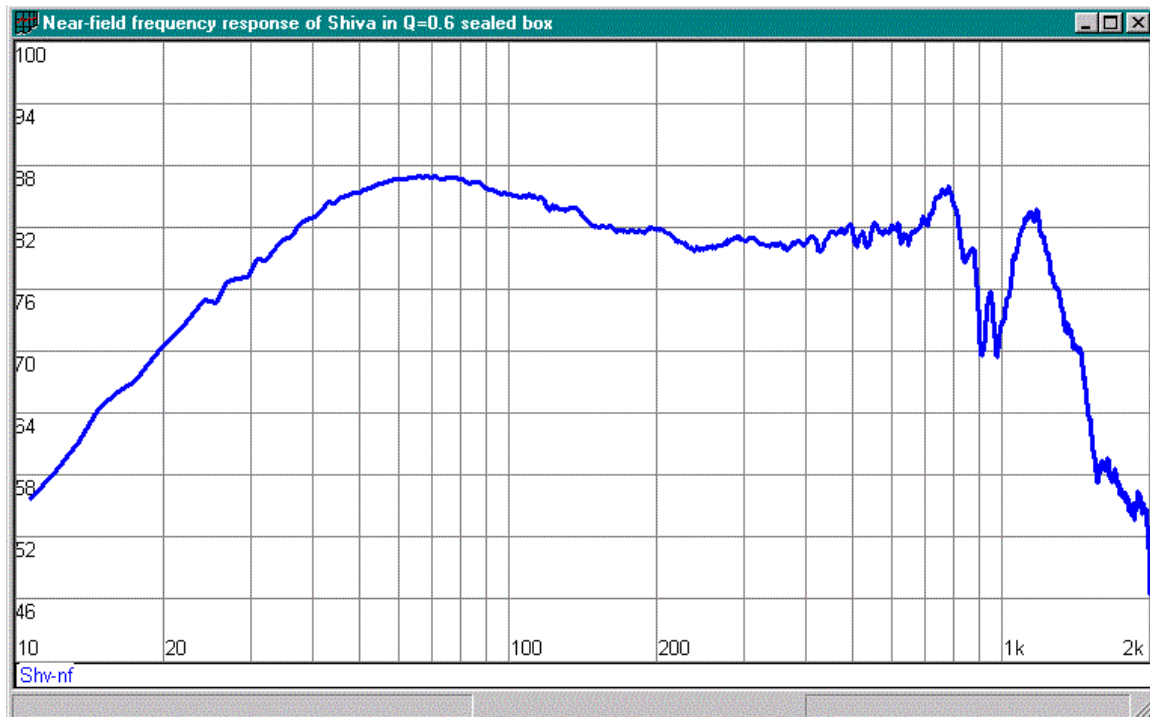


Figure 2 - Near field frequency response

As can be seen, the low frequency response exhibits a typical $Q=0.6$ curve; realize that the low-frequency end of the response is completely determined by the alignment used for the driver. Additionally, the “bump” in the low end of the response (from 40 Hz to 150 Hz) is an artifact of the near-field response measurement, and is expected.

The high frequency response of the driver shows a peak at 780 Hz. This is the primary breakup mode of the driver. Additional breakup modes are seen at 900 and 990 Hz (destructive), and 960 and 1150 Hz (constructive).

Based upon the measured frequency response, we recommend that the bandwidth of Shiva be limited to below 450 Hz. This will keep the breakup modes greater than 20 dB down, assuming use of a 4th order lowpass filter at 450 Hz, with $Q = 0.707$. Note that a lower-order crossover can be successfully used, provided the crossover frequency is lowered as well (for example, a first order electrical network will provide the recommended amount of attenuation if set to roughly 75 Hz).

1.5 Impedance

The Shiva impedance was measured in a $Q=0.6$ (88.5 liter) enclosure. Impedance was measured for a single coil. This measurement is fairly representative of the impedance of a sealed-box Shiva system, and is a good indicator of the type of load such a system will place on either a passive crossover or high-output-impedance amplifier. The measured impedance is:

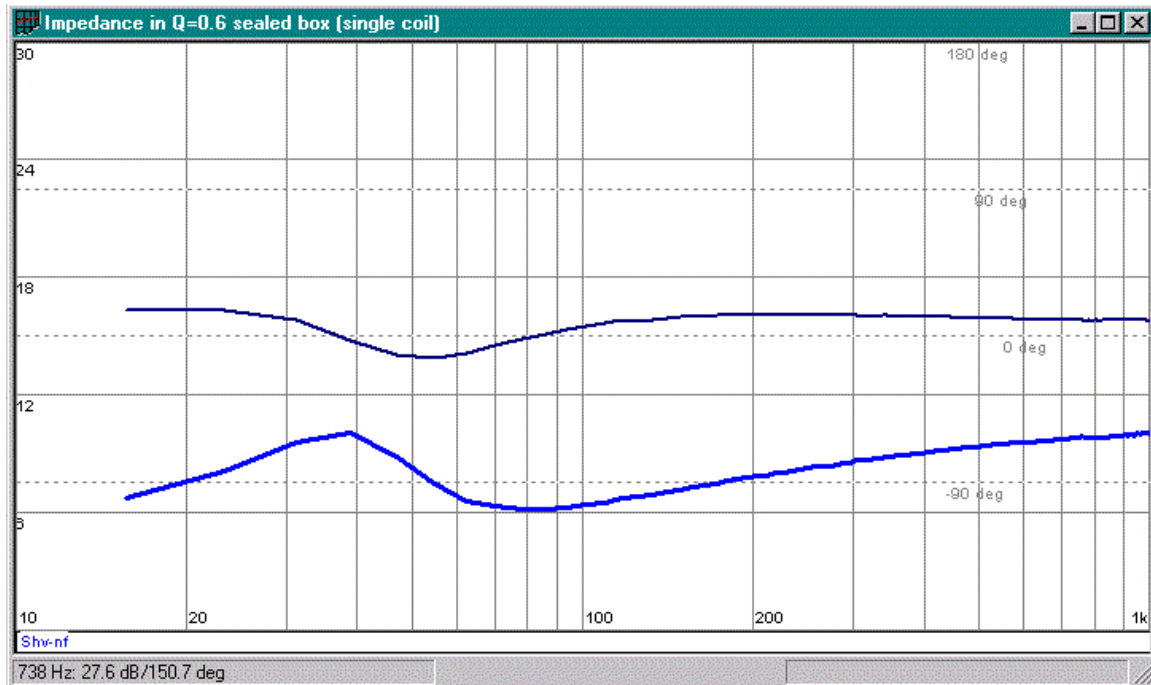


Figure 3 - Impedance of $Q=0.6$ box

The impedance presented by the in-box Shiva is quite benign; the minimum (per coil) is 6Ω , while the maximum level is 10Ω . This impedance curve is well-suited to approximation as an 8Ω load. Additionally, the phase exhibits less than 30 degrees of phase shift throughout the passband.

2 Physical Construction

2.1 Cone

The cone of Shiva is made from Kevlar™-impregnated paper, and is treated with a stiffening epoxy. This combination creates a very stiff material with good internal damping. It is formed into a woofer diaphragm having the optimal cone angle to maintain piston motion up into the midrange, making it easy to cross over to the next driver.

2.2 Surround

The surround is a thick (1.6mm) compressed foam unit, with a diameter of 25.4mm. The surround is UV treated for longevity. The roll is designed to allow extreme excursions with minimal distress. In combination with the sturdy foam, this prevents the "suck-back" seen in other loose or soft surrounds used in other designs. In addition, this heavy foam provides improved, long-lasting centering and proper termination for the stiff cone.

2.3 Spider

The spider is a flat progressive cloth unit. The spider is gapped from the basket with a custom plastic spacer ring. This arrangement makes for perfectly symmetrical properties, thus linearizing motion over that of common cupped spiders. The progressive design retains a nearly constant compliance until it approaches maximum excursion, at which point it decreases progressively to control excursion beyond Xmax.

2.4 Basket

The driver basket is a thick (15 AWG/B&S) stamped steel unit, with integral ribs to stiffen it. It has a surface area of 760 cm², compared to 500 cm² for a typical "Venezuelan style" cast basket. Thus, it can transfer and radiate heat nearly as effectively as the cast basket, without being as brittle. It is painted with a satin black enamel.

2.5 Former

The former is 2" in diameter. It is made of Kapton™, a heat-resistant, high-strength, non-conductive polymer.

2.6 Voice Coils

The voice coils are 2" in diameter. They are wound with 27 gauge round enamel coated solid core copper wire. Each voice coil is two layers; this yields a total of four layers on the former. The voice coil windings cover 38.14mm of the former.

2.7 Tinsel Leads

The Tinsel Leads are fashioned from low-resistance braided tinned copper and cotton. They are designed to eliminate cone slap while still allowing a full 22mm excursion each side of center.

2.8 Pole Piece

The pole piece is machined from steel. It features a 6.35mm extension past the top plate. This increases the BL linearity and reduces inductance modulation over the specified excursion, yielding the large X_{max} of the driver.

The extended pole piece is also drilled through with a 25.4mm diameter axial vent. This vent, along with the top extension, significantly increases heat conduction away from the voice coil, thus improving power handling and reducing heat-induced power compression.

2.9 Top Plate

The top plate forms the gap of the magnetic circuit. It is machined from steel and is 7.94mm thick.

2.10 Magnet

The magnet consists of two rings of a high-energy ceramic material with a total height of 28.58mm. Total weight is 60 ounces.

2.11 Back Plate

The back plate is stamped from 6.35mm thick steel. It features a rearward-extended bump of 26mm height for increased excursion capability. This thick plate serves both to conduct magnetic flux from the magnets to the pole piece and as a heatsink to radiate heat from the voice coil conducted back down the pole piece.

2.12 Gap

The gap height is set by the thickness of the top plate and is thus 7.94mm thick. The gap width is 1.05mm. The materials and dimensions of the parts that form the gap (pole piece and top plate) were designed through advanced finite-element analysis to create as saturated a gap and as focused and symmetric a field as are possible without sacrificing other important features.

Gap saturation is important to minimize modulation of the magnetic field caused by currents through the voicecoil. Measurements indicate that this was essentially achieved in the Shiva design. Decreased stray field and greatly increased symmetry maximize driver linearity and thus reduce distortion.

3 Theory of Design

Shiva was designed to produce awesome, clean bass in small boxes at a great price. Design choices were made to optimize function over form; if a design change had no positive impact on the performance of the driver, then it was dropped. The result is a high-performance woofer with superior performance at a cost-conscious price.

3.1 Why these T/S parameters?

The T/S parameters of Shiva are quite different from most high-end subwoofers. Most immediately notice the mid-value Qes and the much smaller Vas, then ask the question “why these parameters?”

We wanted a driver with great performance in a small sealed box (57 liters [2 ft³] or smaller), or a medium-sized vented box (less than 120 liters [4.3 ft³]). To determine how to achieve this, we created a simulation/generation program. This program would generate T/S parameter combinations, calculate sealed box (Q = 0.7) and vented box (Avatar) alignments, analyze the results, and iteratively optimize the parameters for best performance.

Then we judged the “ranking” of the T/S parameter combinations with the following criteria:

1. Bass extension. Lower is better, calculated so that halving the F3 will quadruple the score.
2. Box size. Smaller is better. 120 liters is as big as we wanted to go, as that's about as big as you can get from a single 4'x8' sheet of wood, so there was a penalty for boxes >120 l.
3. Reference SPL. Higher is better.
4. Max SPL output versus frequency (summed 1/3rd octave from 10 Hz to 100 Hz).

These were weighted as 30% extension, 25% SPL, 25% max SPL, 20% box size. We calculated these values for the driver in the sealed and vented boxes. Then the total score of the driver was 55% of the sealed score plus 45% of the vented score.

We ran this simulation for 500,000 T/S parameter combinations. The top 0.05% combinations were surprisingly close to how Shiva turned out: low Fs, middle-value Qes, small Vas. Going with a lower Fs at the given Qes only reduced sensitivity, and didn't give much bass extension; lower Qes values increased SPL, but also increased F3 for the boxes; smaller Vas just reduced SPL as expected.

In the end, the target was an Fs around 20 Hz, Qes around 0.4, Qms around 5.0, and a Vas around 150 liters. A Qms of 5.0 or higher had little impact on the Qts, and it's easier to get a higher Qms than a lower one, so if something had to give, it would be Qms.

Then Xmax and power handling came up. Our driver engineer had already discussed with us a possible way to create a design capable of over ±14mm Xmax, so we asked for it. Power handling was spec'd as “high as possible”.

We ended up with Shiva: very good performance in a variety of alignments (the Qts of 0.4 looks promising for TL use, too). Small mid-Q sealed boxes (42 liters stuffed for Q=0.7 F3 = 42.2 Hz, F8 = 17.8 Hz). TINY medium-high-Q sealed boxes (22 liters stuffed for Q=0.9, F3 = 39.8 Hz, F8 = 20 Hz). Medium to large vented boxes (anywhere from 50 liters to 150 liters).

3.2 *Why dual voice coils?*

After asking about the T/S parameters, the next most common question is “why dual voice coils?” Most high-end subwoofers have a single voice coil; so why dual?

Simply put, dual voice coils dramatically increase the flexibility of the driver. Most obviously, the total impedance of the driver can be changed. As each voice coil is nominally 8Ω , one can run a single voice coil and have a nominal 8 ohm woofer. But wiring the voice coils in parallel will yield a nominal 4Ω woofer. And wiring the voice coils in series will yield a nominal 16Ω woofer. All in all, these configurations allow easy use in low-voltage applications (4Ω woofer, for use in apps such as car audio), or multiple driver systems (16Ω drivers allow one to parallel 2 to 4 drivers in a single system, and still maintain an acceptable impedance without series connecting any drivers).

Note that the connection flexibility afforded by dual voice coils is equally great. For example, to use a single channel of an amplifier (or a monoblock amplifier), one can connect the voice coils in parallel or series (or just hook up a single voice coil) to meet the load requirements of the amplifier.

But, to use a stereo amp, one can connect a single voice coil to each channel. This allows the driver to act as the “summing” junction of a stereo signal, mechanically summing the stereo signals into a “mono” driver. One does not need to electronically sum the channels together. This dramatically eases applications where passive crossovers are used.

But the most important benefit for dual voice coils is flexibility for the T/S parameters. One can actually “dial in” a desired Qts of the driver, by resistively loading one voice coil and actively driving the other.

This configuration, which we call **Resistively Damped Operation (RDO)**, uses the second (undriven) voice coil as an electromagnetic brake. In essence, the resistance across the second coil will determine how strong the brake is. The smaller the resistance, the stronger the brake.

RDO affects the Qts of the driver by decreasing the Qms of the driver. The RDO brake acts to damp cone motion, as if the suspension was considerably stiffer. However, as it’s an electromagnetic brake, the Fs is NOT affected (as it would raise if the suspension components – the surround and spider – were stiffened).

This allows one to literally “dial in” a desired Qts by varying the Qms of the driver. In fact, a $250\ \Omega$ 5W potentiometer can be used to tune Shiva over a large range. For example, placing Shiva in an 80 liter box, and using the RDO configuration, one can dial in a system Qtc ranging from 0.55 to 1.1. This allows tailoring the low-end response of the system to meet most musical/home theater reproduction needs.

3.3 Why a steel basket?

Many consider a cast basket as superior to a steel basket. In reality, a well-designed steel basket can be as effective as a cast basket. Let's review what a speaker basket should do:

- A basket is the foundation of the speaker. All parts are attached to the basket, in one way or another. The basket is responsible for holding all the moving parts in alignment with each other. Therefore a basket should be stiff (to handle the motion of the cone) as well as precision made (to keep everything in alignment).
- The basket also aids cooling of the system. Dynamic (moving cone) drivers are very inefficient. A full 99%+ of the power delivered to the driver is dissipated by the voice coil as heat. It's really up to the basket (along with the motor structure) to help dissipate this heat, to keep things from overheating.

So, in light of this information, why did we choose a stamped steel basket and not a cast aluminum basket? Let's address each issue one at a time.

A basket should be stiff. The basket used in Shiva is more than stiff enough. It's made of 15AWG/B&S gauge steel, which has a modulus of elasticity of greater than 84,000,000 kg per cm². Aluminum alloys tend towards a modulus of elasticity of 30,000,000 kg per cm². In terms of elasticity, steel is better than aluminum. To get the required strength out of an aluminum frame requires more aluminum, which unnecessarily adds cost to the driver.

A basket should be precise. Stamping is a process that allows great accuracy in the stamped part's dimensions. The stamping process used results in alignments of angles, location of centers of radii, etc. to better than 0.1%. Additionally, stamping has been a proven technology for precision applications (automotive/aerospace). Cast can offer greater tolerances, but both technologies are more than accurate enough for driver applications.

That leaves heat dissipation. Aluminum has better heat conduction than steel. However, the ability to dissipate heat is a function of surface area as well. The wide ribs of the stamped steel basket dissipate nearly as much heat as a typical "narrow" armed cast basket. In fact, the surface area of the Shiva basket is roughly 52% greater than a typical cast basket. And the rated (and fully tested) maximum power handling of 600W Shiva indicates that power dissipation is not an issue.

Overall, a cast aluminum basket doesn't have real-world advantages over a well-designed steel basket. In addition, the cast basket costs more.

3.4 Why a foam surround?

We chose a foam surround based on the requirement for large X_{max}. Simply put, available rubber (natural and synthetic) surrounds did not provide the long X_{max} (or X_{sus}) needed for Shiva. Going with a rubber surround would have removed several mm from both specifications, and would have run counter to the concept of Shiva being an extremely long-throw subwoofer.

Additionally, thin and loose surrounds, both foam and rubber, can experience "suck back" at high SPLs when the negative pressure (relative to ambient outside pressure) inside the box literally pulls the surround backwards, flipping it inside out and quickly destroying it. To avoid this effect, the surround must be made thick. However, synthetic and rubber surrounds of sufficient thickness to avoid this problem would have added dramatically to the stiffness of the suspension, resulting in a much higher F_s. The foam material used on the Shiva surround allows for sufficient thickness to avoid suckback, but without the negative effects of a much stiffer suspension.

Some people may be concerned about the reliability/longevity of the foam surround. The foam surround used in Shiva is fully UV resistant, and should exhibit a lifespan of considerably longer than 10 years.

4 Applications

4.1 Power Amplifier Selection

At first glance, Shiva would seem to indicate a need for a 600W amplifier, since that's the power rating of the driver. However, this is not the case. Very good results can be achieved with Shiva running from as little as 40W per channel. Even smaller amplifiers (10WPC) can result in a musically satisfying experience. It really depends upon your tastes and the capabilities of the loudspeakers paired with Shiva.

The 600W rating of Shiva is just that; a maximum power rating. This is the peak amount of power that can be dissipated in Shiva over the long term. Realize that this level of power would yield an in-room output in the 120 dB SPL range; this level is well beyond the typical continuous home listening environment.

However, assuming a source peak-to-average ratio of 15 dB (such as is typical for modern music or FM broadcasts), listening at normal levels (90 dB SPL) would require peaks of 105 dB SPL. This peak level requires 17.5 dBW, or 56.2W of amplifier power. As such, most home receivers capable of 100W per channel performance will be quite suitable for use with Shiva.

We do realize that such listening levels (90 dB SPL nominal) are not for everyone. Some individuals will listen to Shiva at higher levels. The 600W rating is intended to allow for those who enjoy musical peaks up to and beyond 120 dB SPL in-room.

As with all acoustic transducers, we strongly recommend that you exercise good judgement when listening to your loudspeakers. High power/high SPL capable drivers such as Shiva can cause permanent hearing damage and actual hearing loss, if abused. Prolonged exposure to levels in excess of 110 dB can cause partial or full deafness. Be kind to your ears!

4.2 Mounting

Many low-Fs drivers cannot be mounted in a downfiring (or horizontal) configuration; they must be oriented vertically, with the cone/basket perpendicular to the floor. To achieve a very low Fs in other subwoofer systems, the moving mass of the system is made quite high, while the stiffness of the suspension is made low. These two changes work to create a system which will suffer excessive cone offset when mounted so that gravity will pull the cone out, away from the normal "rest" position.

Because Shiva has an Fs of 21.6 Hz, the moving mass is not substantially more than competitive subwoofers. However, the surround is considerably stiffer. This results in Shiva being rated for horizontal mounting. In fact, given the T/S parameters, one can calculate the effective loss in Xmax that will occur due to the offset of the cone from the force of gravity:

Basically, one looks at the mass of the cone (118.3 grams, in the case of Shiva), and the mechanical deflection, Cms (0.47 mm/N, as measured by DUMAX). The acceleration of gravity (what's pulling the cone down, or up) is 9.8 m/s^2 .

Now, a Newton (the N in Cms' units) is in units of $\text{kg} * \text{m} / \text{s}^2$, or kilogram meter/second squared.

So, multiply the mass of the cone by the force applied (gravity) by the mechanical deflection:

$$\text{mass} * \text{force} * \text{deflection} = 0.1183 \text{ kg} * 9.8 \text{ m/s}^2 * 0.47 \text{ mm/N}$$

$$= 1.1593 \text{ kg} * \text{m} / \text{s}^2 * 0.47 \text{ mm} / (\text{kg} * \text{m} / \text{s}^2)$$

Note that there's a $\text{kg} * \text{m} / \text{s}^2$ term in the numerator and the denominator. Cancel the units out, and you're left with 0.545 mm. Thus when Shiva is mounted horizontally, one will end up with an Xmax of 14.355mm one way (in the direction of gravity), and 15.44mm in the opposite way. As a comparison, several other high-end 12" subwoofer drivers will exhibit up to 1mm of offset; considering these units typically start with 2-mm less Xmax than Shiva, the result is a considerable drop in swept volume.

4.3 General Alignment Notes

Shiva was designed to be a very versatile subwoofer driver, allowing numerous different acceptable bass alignments, depending on the characteristics desired of the system. In describing these enclosures and tunings, the following will be calculated for each alignment so that the responses can be compared:

- Box volume. The net internal volume, without any stuffing. Stuffed boxes can be from 10% to 25% smaller, based upon bandwidth of the signal and the stuffing density.
- Fb, the resonant frequency of the system. This is the nominal tuning frequency of the enclosure.
- Anechoic F3, the half power point of the system, in full space, referenced to the peak output.
- Anechoic F8, the apparent half volume point of the system, in full space, referenced to the peak output.
- Anechoic >100 dB SPL, the frequency above which the system is capable of greater than 100 dB SPL in full space.
- In Room F3, the predicted half-power point of the system, referenced to the peak output, when corner loaded in a 50m³ room (4m x 5.5m by 2.3m).
- In Room F8, the predicted apparent half volume point of the system, referenced to the peak output, when corner loaded in a 50m³ room (4m x 5.5m by 2.3m).
- In Room > 105 dB SPL, the frequency above which the system is capable of greater than 105 dB SPL, when corner loaded in a 50m³ room (4m x 5.5m by 2.3m).

Note that the frequencies are referenced to the peak output of the system, not the nominal output. Thus, increasing any peak in the output frequency response, e.g. increasing the Q of a sealed box, can result in a higher actual F3, not a lower F3. We choose to use this reference (peak versus nominal) because for higher Q systems, the nominal output is not achieved until several hundred Hertz (>200 Hz). We believe this is not applicable to subwoofers. As such, the F3 should be referenced to the highest value below 100 Hz.

When placed in a room, effective bass output increases considerably due to room loading. Thus 105 dB SPL is selected as a "reference" level representing a very loud signal. This is also the typical maximum SPL level required by several home theater specifications.

4.4 Sealed Enclosures

Because of middle the EBP value (~55), Shiva is a natural driver for use in sealed boxes. Additionally, the lower Vas, as compared to other 12" subwoofers on the market, allows use of less-intrusive box sizes.

4.4.1 Low-Q Alignments

Many people praise the "tight" sound of low-Q systems (particularly low-Q sealed enclosures and transmission lines. Traditionally, low-Q sealed boxes exhibit a Q of 0.6 or less). Low-Q system adherents claim that the low-Q alignment sounds "most natural". Additionally, some claim it is ideal for classical music reproduction, as any apparent "punch" in the sound would not be desirable with this source material. In addition, low-Q rolloffs tend to naturally complement the room gain in typical home applications, leading to a very smooth in-room response.

Using the DUMAX T/S parameters given in section 1.3, the following low-Q boxes are recommended:

Parameter	Q = 0.6	Q = 0.577	Q = 0.5
Box Volume	88.5 liters	101.5 liters	178 liters
Fb	34.5 Hz	33.1 Hz	28.7 Hz
Anechoic F3	47.2 Hz	53.1 Hz	63.1 Hz
Anechoic F8	16.8 Hz	17.8 Hz	17.8 Hz
Anechoic >100 dB SPL	22.4 Hz	22.4 Hz	22.4 Hz
In Room F3	26.5 Hz	26.6 Hz	23.7 Hz
In Room F8	11.9 Hz	11.2 Hz	9.4 Hz
In Room >105 dB SPL	18 Hz	18 Hz	18 Hz

Table 2 - Low Q sealed alignments

Of particular interest is that the anechoic F8 of these systems are all below 20 Hz. This promises very deep bass response. The numbers from the in-room simulations confirm this, showing that response well down to the mid-to-lower 20s for half power, with the apparent half volume level in the 10 Hz range. Note that the frequencies are referenced to the peak output of the system, not the nominal output, as described at the top of this section.

Additionally, note that each system is capable of more than 100 dB SPL from 22.4 Hz and up in free air (i.e. anechoic, not in-room). This number does not change with alignment, as it is strictly a function of how much air Shiva can move. Thus, with equalization, one could get flat response from any of these alignments, at 100 dB SPL, from 22.4 Hz and up. This is a very high level of output.

In-room maximum SPL is even higher, with sealed Shiva systems capable of greater than 105 dB SPL from 18 Hz and up. This level of performance exceeds the limits required by several home theater specifications.

The following graph displays the typical in-room (corner-loaded) response of each system, when driven through a 4th order $Q=0.707$ lowpass filter set to 80 Hz. Delivered power is 1W into a nominal 4Ω load ($2V_{RMS}$ drive level). The $Q=0.6$ box is shown in green. The $Q=0.577$ box is shown in blue. The $Q=0.5$ box is shown in red.

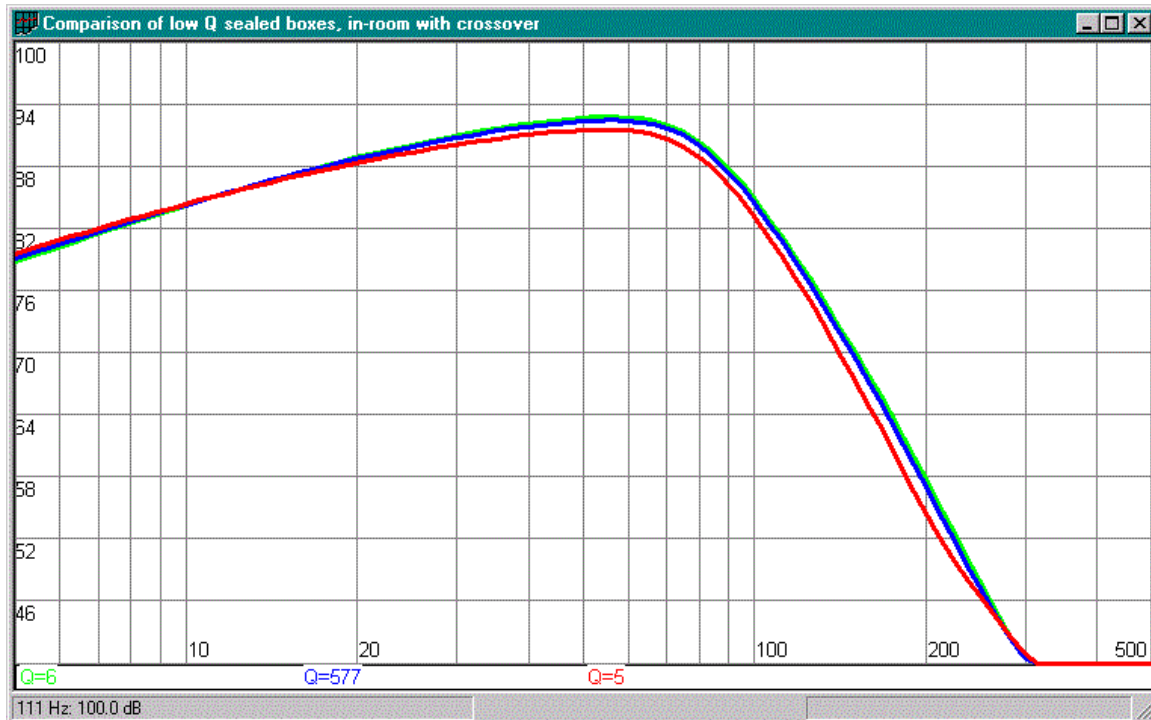


Figure 4 - Low Q box responses

As can be seen, the performance of all three, in terms of frequency extension, is nearly identical. It is on this basis that, for low Q alignments, we recommend the $Q=0.6$ box. Frequency response is not compromised, and the $Q=0.6$ box is physically the smallest of the three.

4.4.2 High-Q Alignments

High-Q systems are described by a Q greater than or equal to 0.707. These responses may have a bit of a bump in the passband. High-Q adherents prefer the extra “punch” one gets from the bump in the midbass. Additionally, high-Q systems are typically recommended for pop/rock music reproduction, as well as use in home theater applications.

Using the DUMAX T/S parameters given in section 1.3, the following high-Q boxes are recommended:

Parameter	Q = 0.707	Q = 0.85	Q = 0.95
Box Volume	54 liters	33.3 liters	25.5 liters
Fb	40.6 Hz	48.8 Hz	54.5 Hz
Anechoic F3	39.8 Hz	39.8 Hz	39.8 Hz
Anechoic F8	17.8 Hz	20 Hz	21 Hz
Anechoic >100 dB SPL	22.4 Hz	22.4 Hz	22.4 Hz
In Room F3	29.8 Hz	33.5 Hz	37.6 Hz
In Room F8	14.1 Hz	18 Hz	20 Hz
In Room >105 dB SPL	18 Hz	18 Hz	18 Hz

Table 3 - High Q sealed alignments

Note that for the Q=0.707 and the Q=0.85 alignments, deep bass performance is still achievable (with the in-room apparent half volume frequency still around 20 Hz). And the boxes are considerably smaller, ranging from just under 2 cubic feet (Q=0.707) to just under one cubic foot (Q=0.95).

The Q=0.95 box trades some bass extension for small size. It would be the alignment most likely to benefit from active equalization (such as the Linkwitz Transform Filter). In such cases, the bass can be extended down to the upper 20 Hz range in-room, yet the overall box size is kept to an absolute minimum.

Additionally, the Q=0.95 box would be ideal for use in car, where the gain of the car cabin is considerably higher than that for a home room. In this application, the apparent half volume point (in room F8) would be well below 20 Hz.

The 100 dB SPL (anechoic) and 105 dB SPL (in-room) levels are unchanged as compared to the low-Q sealed boxes. This again reinforces the fact that maximum SPL is purely a function of the displacement of the system. Since all sealed systems utilize the driver by itself as the displacement piston, this becomes the limiting factor.

The following graph displays the typical in-room (corner-loaded) response of each system, when driven through a 4th order $Q=0.707$ lowpass filter set to 80 Hz. Delivered power is 1W into a nominal 4Ω load ($2V_{RMS}$ drive level). The $Q=0.707$ box is shown in green. The $Q=0.85$ box is shown in blue. The $Q=0.95$ box is shown in red.



Figure 5- High Q box responses

As can be seen, the performance of the $Q=0.707$ box, in terms of frequency extension, is considerably better than the other two options. It is on this basis that, for high Q alignments, we recommend the $Q=0.707$ box. This box will have the best in-room extension, and is not appreciably larger than the other alignments.

4.5 Vented Enclosures

Because of the mid-value EBP (55) of Shiva, some vented alignments are possible. Additionally, the large Xsus of Shiva helps reduce concern over woofer unloading below the tuning frequency.

Several potential alignments are provided, ranging from the traditional SBB4 alignment, to an Extended Bass Shelf alignment, to the proprietary Avatar Audio alignment.

Parameter	SBB4	EBS	Avatar
Box Volume	100 liters	165 liters	85 liters
Fb	22.1 Hz	16.5 Hz	20 Hz
Recommended Vent	4"D by 16.75"L	4"D by 18"L	4"D by 24.75"L
Anechoic F3	23.7 Hz	28.2 Hz	28.2 Hz
Anechoic F8	18.8 Hz	14.1 Hz	18.8 Hz
Anechoic >100 dB SPL	17.8 Hz	16.8 Hz	16.8 Hz
In Room F3	23.7 Hz	17.8 Hz	26.6 Hz
In Room F8	18.8 Hz	13.3 Hz	18.8 Hz
In Room >105 dB SPL	16.3 Hz	13.3 Hz	15.8 Hz

Table 4 - Vented alignments

In these systems, the vent is given in inches, as is used for standard ABS plumbing pipe. Note that the frequencies are referenced to the peak output of the system, not the nominal output, as described at the top of this section.

For all systems, note the relatively small change between anechoic and in-room F3 and F8 frequencies, as compared to the sealed systems. This is typical of vented (and other higher order) systems. The impact of the room on bass extension will be minimal with such systems; rather, the main benefit from the room interaction is the notable increase in maximum SPL.

Of the three systems, the EBS provides the most bass extension, albeit with the largest box. The EBS also provides the most SPL output, exceeding 100 dB anechoic and 105 dB in room at 16.8 Hz and 13.3 Hz, respectively.

The SBB4 provides decent bass extension (in-room response to the low 20s). This traditional alignment also provides good SPL output, exceeding 100 dB SPL at 17.8 Hz anechoically, and 105 dB SPL at 16.3 Hz in-room.

The Avatar alignment provides almost all the apparent bass extension of the SBB4 box, but in a smaller box. Also the Avatar alignment has a wider spread of F3 to F8, indicating a shallower "knee" in the response curve. Lastly, due to the lower tuning of the Avatar alignment, the 100-dB SPL anechoic frequency is the same as the EBS alignment (both of which are better than the SBB4 alignment). And the 105 dB SPL in-room limit is lower than the SBB4 as well. The tradeoff is a longer vent (8" longer as compared to the SBB4).

Overall, the vented boxes do not provide the same in-room bass extension as a sealed box. However, the maximum SPL output is considerably higher than the sealed boxes. Additionally, bass extension is quite good, with output into the 20 Hz region. As low frequency response extension can be increased with equalization, max SPL capability becomes important. It is in this light that the vented box excels.

The following graph displays the typical in-room (corner-loaded) response of each system, when driven through a 4th order $Q=0.707$ lowpass filter set to 80 Hz. Delivered power is 1W into a nominal 4Ω load ($2V_{RMS}$ drive level). The SBB4 box is shown in blue. The EBS box is shown in green. The Avatar Alignment box is shown in red.



Figure 6 - Vented box responses

As can be seen, the EBS alignment clearly has the best frequency extension of all the vented boxes. Next, the Avatar Alignment has a slight edge over the SBB4 in terms of deep bass frequency response, but uses a 15% smaller box. Overall, the EBS provides the best performance, with the Avatar Alignment second. Therefore, if size is not an issue, we recommend use of the EBS box. However, if size is of concern, clearly the Avatar Alignment is preferred over the SBB4, as it has superior deep-bass extension in a smaller box.

4.6 Passive Radiator Systems

Passive radiators (PRs) are often used as a vent replacement, where the length of a large-diameter vent becomes impractical to build. In such cases, a PR can be a suitable substitute. Additionally, there is some data backing the thought that a PR system will avoid the complete driver unloading of a typical vented system when run below Fb.

As PRs can be considered vent replacements, we will use the three alignments in the vented section. In these cases, the vent is replaced by a single Avatar Audio PR-15 (a 15" passive radiator, with 431 grams of moving mass). Tuning is via added weight to the diaphragm.

Parameter	SBB4	EBS	Avatar
Box Volume	100 liters	165 liters	85 liters
Fb	22.1 Hz	16.5 Hz	20 Hz
Necessary extra mass	34 grams	77 grams	250 grams
Anechoic F3	23.7 Hz	28.2 Hz	28.2 Hz
Anechoic F8	18.8 Hz	14.1 Hz	18.8 Hz
Anechoic >100 dB SPL	17.8 Hz	16.8 Hz	16.8 Hz
In Room F3	23.7 Hz	17.8 Hz	26.6 Hz
In Room F8	18.8 Hz	13.3 Hz	18.8 Hz
In Room >105 dB SPL	16.3 Hz	13.3 Hz	15.8 Hz

Table 5 - Passive radiator alignments

The parameters are the same as given above. The extra mass is the amount of mass needed to tune the Avatar PR-15 to the appropriate Fb. The frequencies are referenced to the peak output of the system as before.

The acoustic performance of a PR system is very similar to a vented system. However, a PR system is a higher order system, and therefore exhibits a notch in frequency response at twice the resonant frequency of the passive radiator. As the PR-15's natural Fs is 7.76 Hz, and adding mass to the PR-15 will only lower the Fs, this notch will typically be below 16 Hz, which should prove to be audibly benign. In fact, the PR-15 (which can have a total moving mass of 1,000 grams, implying up to an extra 569 grams of mass) makes it possible to create alignments with Fb below 13 Hz, reducing audible group delay to a minimum. The EBS alignment above is like this with its 16.5 Hz tuning.

Overall, PRs perform as well as vented boxes, with three major advantages: ease of tuning by the simple addition or removal of mass rather than the cutting of a vent, no vent noise from vent self-resonance or chuffing, and protection for driver unloading below Fb.

Graphs of response are not shown for the PR alignments as the predicted results will closely match that of the vented alignments on which the PR designs are based. Additionally, conclusions drawn for the vented alignments also apply to the PR designs.

4.7 Band Pass Enclosures

Band Pass boxes (BP) use two acoustic filters for the driver. All other alignments so far discussed use a single high-pass acoustic filter for the driver, with the driver directly radiating into the room. A BP box adds a low pass acoustic filter to the equation. In this manner, the high frequency output of the system can be reduced. Also, the passband sensitivity can be increased. This low-pass acoustic filter is implemented via a vented chamber on the front of the driver (this vent can also be implemented via a passive radiator, and will result in the gains afforded to PR systems such as reduced excursion below resonance, no vent self-noise). As such, the driver itself does not directly radiate into the room; rather, the output of the low-pass acoustic filter provides all system output.

Three 4th order BP boxes are given; S=0.7, 0.6, and 0.5. These different S alignments will result in progressively wider bandwidths, but at the cost of efficiency and passband ripple. In all cases, the lower frequency was set to 20 Hz.

Parameter	S=0.7	S=0.6	S=0.5
Rear Box Volume	83.8 liters	62 liters	45.8 liters
Front Box Volume	37.9 liters	27.9 liters	19.4 liters
Front Tuning Frequency	35 Hz	38.7 Hz	43.1 Hz
System Gain	-2.73 dB	-3.68 dB	-4.97
Anechoic Low F3	20 Hz	20 Hz	20 Hz
Anechoic Low F8	16.5 Hz	16.5 Hz	16.5 Hz
Anechoic High F3	62.3 Hz	75.1 Hz	89.1 Hz
Anechoic High F8	77.6 Hz	92.3 Hz	106 Hz
Anechoic >100 dB SPL	18.8 Hz	18.8 Hz	18.8 Hz
In Room Low F3	20 Hz	20 Hz	20 Hz
In Room Low F8	15.8 Hz	15.8 Hz	15.8 Hz
In Room High F3	59.6 Hz	70.8 Hz	89.1 Hz
In Room High F8	75.1 Hz	89.2 Hz	106 Hz
In Room >105 dB SPL	14.2 Hz	14.2 Hz	14.2 Hz
Nominal passband sensitivity	84.5 dB @ 1W	83.5 dB @ 1W	82.2 dB @ 1 W

Table 6 - Bandpass alignments

The three bandpass options show the range of bandwidths and gain that one gets with different bandpass alignments. From the calculated results, it is easy to see that the bandwidth in a relatively small box is gained at the expense of efficiency. For example, the S=0.5 enclosure is a net 65.2 liters; this is on par with the Q=0.707 box, and smaller than any of the vented or PR systems. Yet the bass extension is superior to all the other options.

However, the lost efficiency can be worrisome to many. A loss of nearly 5 dB in overall efficiency is quite a bit; however, considering the power handling capabilities of Shiva, this can be made up, to a large extent, with more power. Realize that using a 314W amplifier with the S=0.5 box will result in the same maximum volume output as using a 100W amplifier with the normal sealed boxes.

The following graph displays the in-room frequency responses of the three different boxes. A 2nd order low pass filter at 80 Hz with a $Q=0.707$ is implemented as well. Note that this filter is considerably shallower than other crossovers implemented in this section; this is a direct result of the low-pass filter nature of the bandpass box not requiring as steep a crossover to adequately attenuate higher frequencies.



Figure 7- Bandpass box responses

The $S=0.7$ alignment (blue) requires the largest box, and yields the narrowest bandwidth. However, it has the flattest response, and the least amount of loss. The $S=0.6$ alignment (green) requires a medium size box, and trades off additional gain for bandwidth, at the expense of introducing ripple in the passband. The $S=0.5$ alignment (red) gains more bandwidth, but loses more efficiency, and has more passband ripple.

Of the three bandpass alignments, the $S=0.6$ is recommended. This alignment provides wider bandwidth in a smaller box when compared to the $S=0.7$ alignment. Additionally, the extra high-end bandwidth offered by the $S=0.5$ alignment is generally not worth the added ripple and resulting degraded transient response offered by the $Q=0.5$ alignment. Lastly, the efficiency loss of the $S=0.6$ alignment is less than 1 dB worse than the $S=0.7$ alignment, but nearly 1.4 dB better than the $S=0.5$ alignment.

Additional tradeoffs with all BP boxes are increased construction complexity and a reputation for “boomy” sound. This characterization of the sound may stem from numerous causes: the increased group delay of BP alignments as compared to simple sealed or vented alignments, the complexity of building and tuning properly, the altered sensitivity increasing decreasing the level of bass to treble, and from incorrect “drop-in” commercial bandpass boxes. However, if careful attention is paid to the BP box alignment, this increase in group delay can be minimized to near-inaudible levels.

Overall, the BP box promises the most SPL output of any installation. Its tendency for “boomy” sound, however, may limit its use to where max SPL is the predominant factor in system selection (such as large home theater installations, and high-SPL car audio applications).

4.8 Infinite Baffle and Dipole Designs

Infinite Baffle (IB) and Dipole systems share one common trait: the driver is essentially operating on it's own. There's no real enclosure for the driver. The difference between the IB and Dipole is that for the IB, the backwave is isolated from the frontwave of the driver (think of a huge sealed box, of volume approaching infinity). For a Dipole system (where the baffle has a finite size), the backwave can interact with the frontwave, resulting in a reduction in frequency response.

The IB situation would be applicable when the volume behind the driver exceeds roughly 4 times the V_{as} , or 576 liters. At this point, the Q would be 0.418, extremely close the Q_{ts} of Shiva. While IB is traditionally defined as when $Q_{tc} = Q_{ts}$, we believe that the system is essentially IB when Q_{tc} is within ~10% of Q_{ts} . For Shiva, this means $Q_{tc} \leq 0.418$. IB really represents the low- Q end of the continuum of sub-0.707 Q sealed alignments, with corresponding properties.

For the IB installation, performance would be as follows:

Box volume	576 liters
Q_{tc}	0.418
F_b	24 Hz
Anechoic F_3	84.1 Hz
Anechoic F_8	20 Hz
Anechoic >100 dB SPL	22.4 Hz
In Room F_3	17.8 Hz
In Room F_8	10 Hz
In Room >105 dB SPL	18 Hz

Table 7 - Infinite baffle alignment

Note that the anechoic F_3 is much higher (two octaves) than the anechoic F_8 . This is indicative of a very low Q system. And the in-room response promises extremely good bass extension, with an apparent half volume frequency of 10 Hz. Of all systems given in this paper, the IB has the best bass extension.

To simulate the response of an infinite baffle installation, consider the system as a sealed box with Q_{tc} within 10% of Q_{ts} . For Shiva, this translates to 576 liters, as noted above. Plotting the response of a Shiva in a sealed box of 576 liters, with a 4th order 80 Hz low pass crossover of $Q=0.707$, results in:

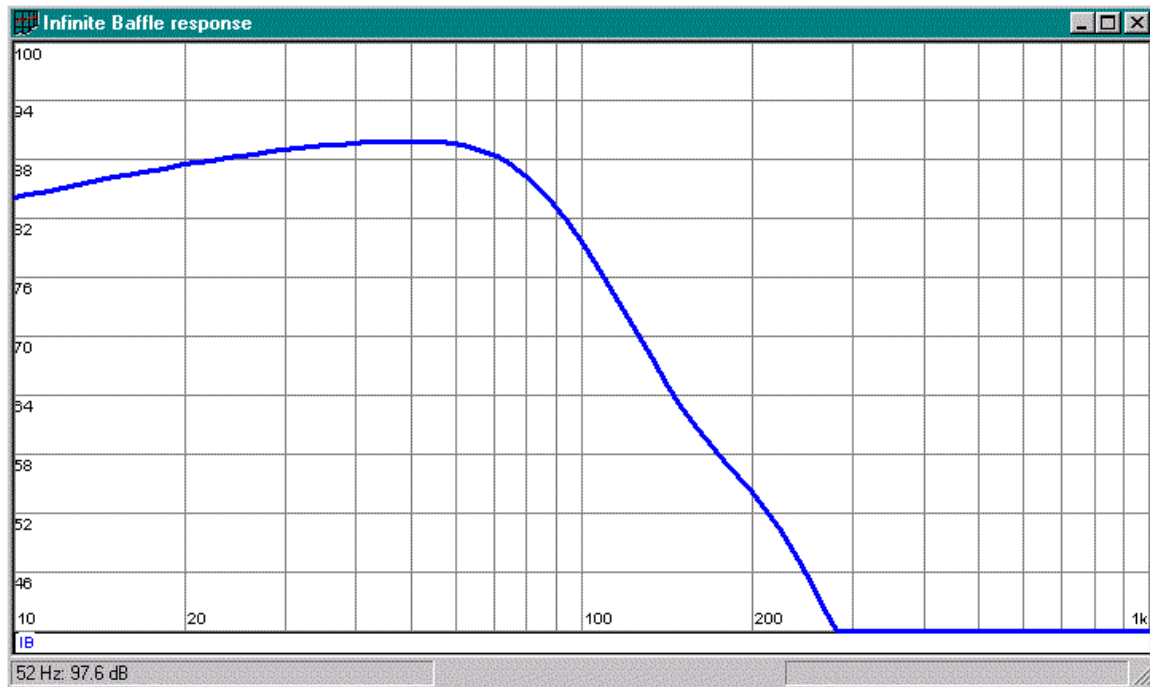


Figure 8- Infinite baffle response

As can be seen, deep bass performance is outstanding, with an F_8 below 10 Hz. Additionally, maximum SPL output in-room is quite good. Overall, the IB system provides the deepest bass capability, with good max SPL, and if the size of the required enclosure can be accommodated, should be seriously considered.

For Dipole systems, prediction of F_3 points becomes difficult due to dependence on a number of factors. The actual frequency response one gets is largely dependent upon the width of the panel in which the driver is mounted due to dipole cancellation causing a 6 dB rolloff dependent on this width, plus the in-room placement of the system. As such, we cannot offer predictions of response output.

Additionally, the maximum SPL one can achieve is also dependent upon the size and shape of the baffle, as well as the rolloff equalization typically used to compensate for the dipole cancellation. However, adherents of dipole installations are quite adamant about the type of sound this system produces, praising its natural “open” sound devoid of boominess.

4.9 Other Response Modifications

4.9.1 Resistively Damped Operation

The dual voice coils in Shiva allow a unique method of tuning to be used to adjust the Qts of the woofer, by operating in a configuration we call Resistively Damped Operation (RDO; see section 3.2). By driving only one coil and wiring a resistor in series with the other, the Qts can be varied between the Qes (0.8 with no connection, i.e. infinite R) and the normal series or parallel Qts (0.39, with R=0, i.e. shorted). This allows passive tuning of a Shiva-based sub after construction, or during the testing phase, to optimize the response in the intended application. Further details will be made available on the Avatar web site (<http://www.avatar.cnchost.com>).

4.9.2 Applying the Linkwitz Transform Filter

The Linkwitz Transform filter offers unique advantages for subwoofer designs by allowing a given system to be transformed into another, at the expense of increased amplifier and driver power requirements. Shiva's high power handling allows this filter to be used successfully in many applications. Future revisions will include this information. Until then, a good discussion of the Linkwitz Transform is given on the TrueAudio web site (<http://www.trueaudio.com/>).

4.9.3 Low Frequency Equalization

A high pass filter can be used to extend the low frequency response of a driver. This equalization takes the form of a $Q > 0.707$ filter (typically a second order high pass network), so that gain is used to extend the response of the entire system. However, using such an equalization places extra demands on the driver. Additional power is dumped into the driver, and since the equalization is typically used below the tuning frequency of the system, this can result in extreme amounts of cone motion.

This is where the extremely long Xmax of Shiva helps out immensely. Because the driver has such a large Xmax, one can extend the response of the entire system quite significantly, and can maintain that flat response to very high SPL levels.

One such application would be with the $Q=0.95$ box given in section 4.4.2. Normally a 25.5 liter box with in-room F3 of 37.6 Hz, this system would not normally be the first system selected for use for high end audio reproduction.

However, placing a 4th order $Q=0.707$ lowpass filter (typical subwoofer crossover) at 80 Hz lowers the in-room F3 to 31.6 Hz. This is because the peak in-room output of the system is shifted down from 96.6 dB SPL @ 1W, 1m at 88.9 Hz to 95.5 dB SPL @ 1W, 1m at 59.4 Hz. Adding a second order high pass filter with $Q = 1.6$ (4.5 dB gain peak) at 13 Hz drops the in-room F3 down to 13.3 Hz. The system is essentially flat from 14 Hz to 70 Hz.

The following graph displays the normal $2V_{RMS}$ (1 Watt into a nominal 4Ω load) in-room response of the system (green), the in-room response of the system with the low pass crossover (blue), and the in-room response of the system with the crossover and equalization (red). As you can see, the equalization turns a normal system, into a true deep-bass reproduction unit.

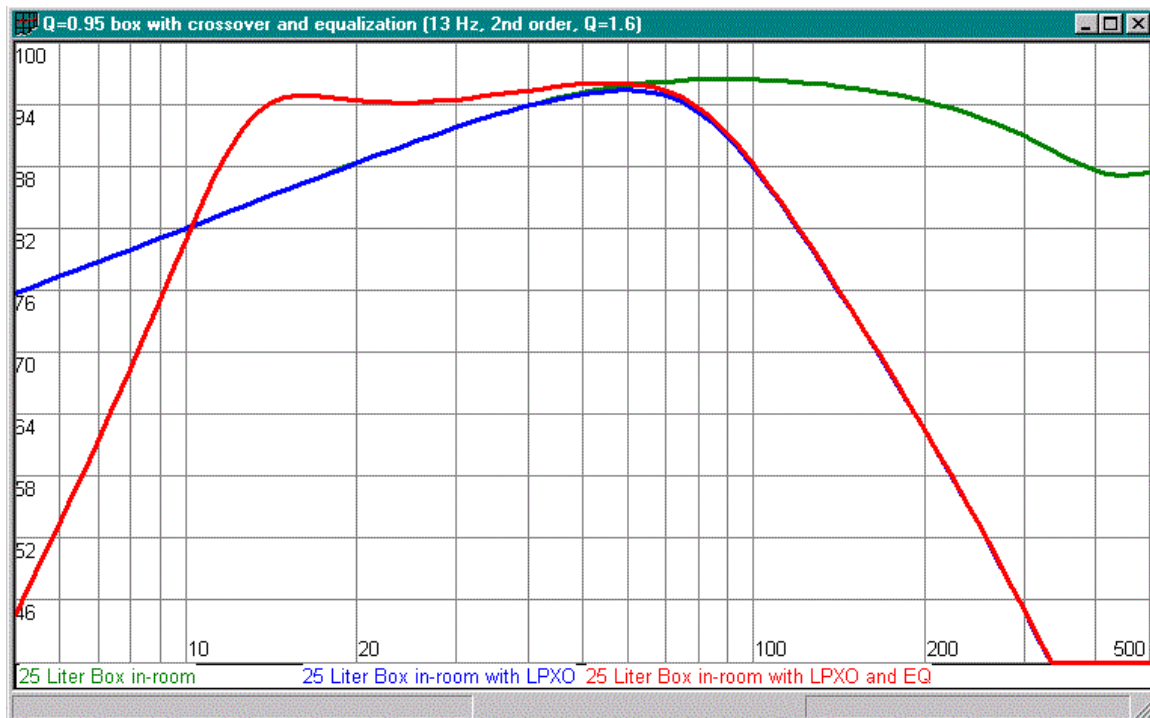


Figure 9 - Equalized small sealed box response

EQ can also be used for vented/PR systems as well. Because of the reduction in cone motion around tuning frequency that a vented/PR system offers, distortion in that region is also lowered. This leads many to consider the vented/PR system as ultimately superior and higher resolution, because of the lower distortion. However, a vented system becomes unloaded below the tuning frequency; a high pass equalization network will reduce the effects of system unloading, by limiting the spectral energy below the corner of the high pass equalizer. In effect, an equalization network for a vented system provides not only response extension/shaping, but also acts to protect the driver from unloading.

As shown in the above sections, vented/PR systems typically lose deep-bass contests to sealed boxes. Judicious application of equalization can help narrow the gap here. This creates an assisted 6th order system, which can result in very good bass extension and tremendous SPL capabilities.

Consider a PR system of 65 liters. The PR is the Avatar PR-15, mass-loaded with 250 grams, for a final tuning frequency of 20 Hz. This represents a small subwoofer that can be easily placed in many rooms. However, as is shown in the table below, the anechoic and in-room frequency response is somewhat lacking, in terms of deep bass extension. By using a second order high-pass filter, set with a corner frequency of 20 Hz and a Q of 1.91, we can dramatically decrease the anechoic and in-room F3 and F8 frequencies:

Parameter	NORMAL	EQUALIZED
Box Volume	65 liters	65 liters
Fb	22.7 Hz	22.7 Hz
Necessary extra mass	250 grams	250 grams
Anechoic F3	29.8 Hz	22.4 Hz
Anechoic F8	22.4 Hz	18.8 Hz
Anechoic >100 dB SPL	17.8 Hz	17.8 Hz
In Room F3	29.8 Hz	22.4 Hz
In Room F8	21.1 Hz	18.8 Hz
In Room >105 dB SPL	16.8 Hz	16.8 Hz

Table 8 -Equalized passive radiator response

As we can see, the equalized response provides bass extension to below 20 Hz; additionally, the frequency extension difference between in-room and anechoic systems does not change, as it is dominated by the equalization of the system itself. This will allow considerable freedom in room placement, as the actual extension will not change with position. Therefore one can position the sub for best integration with the main speakers, and to minimize room modes without concern for loss of bass extension.

The following graph shows the anechoic (blue) and in-room (green) responses of the 65 liter PR system (low pass crossover of 80 Hz, 4th order, Q=0.707). The equalized response (red) is shown as well. As described in the above table, the in-room and anechoic equalized responses are essentially the same (differing only in effective sensitivity, due to the room gain); therefore the in-room equalized response has been chosen for display:

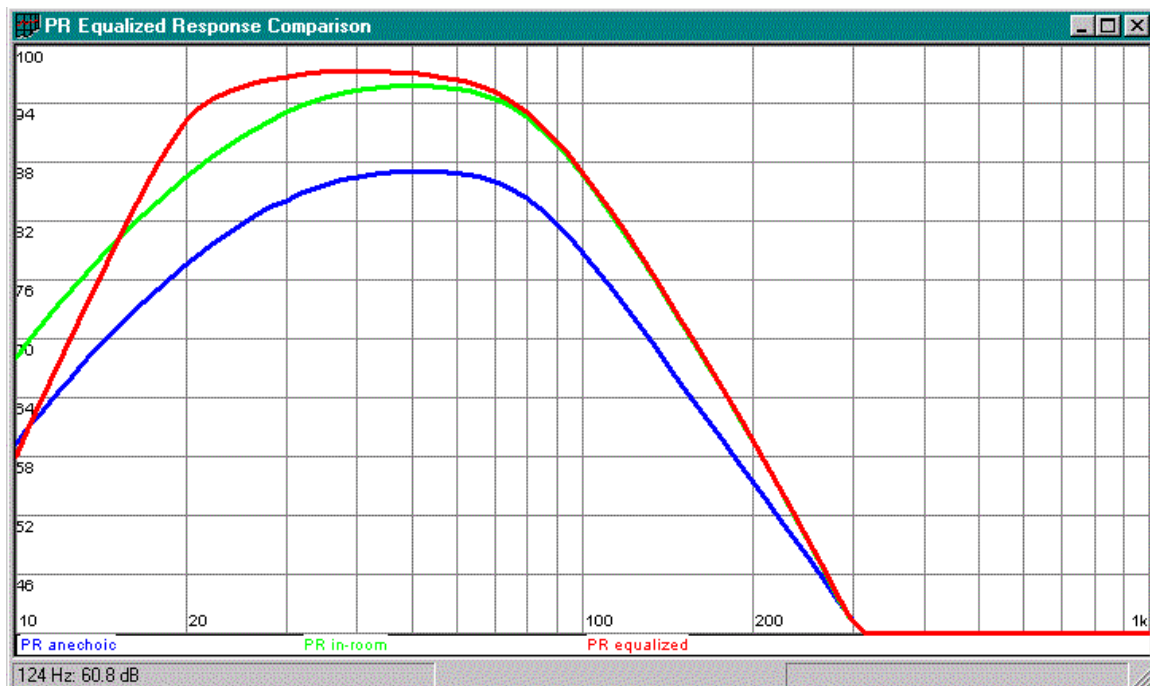


Figure 10 - Equalized passive radiator response

While this system does not have the bass extension of the equalized sealed system, it does provide extension below 20 Hz. Additionally, the maximum SPL of the PR system is considerably higher than that of the sealed system. Following is a graph of the maximum SPL of the equalized sealed box (blue) and the PR systems (red), as described in this section:

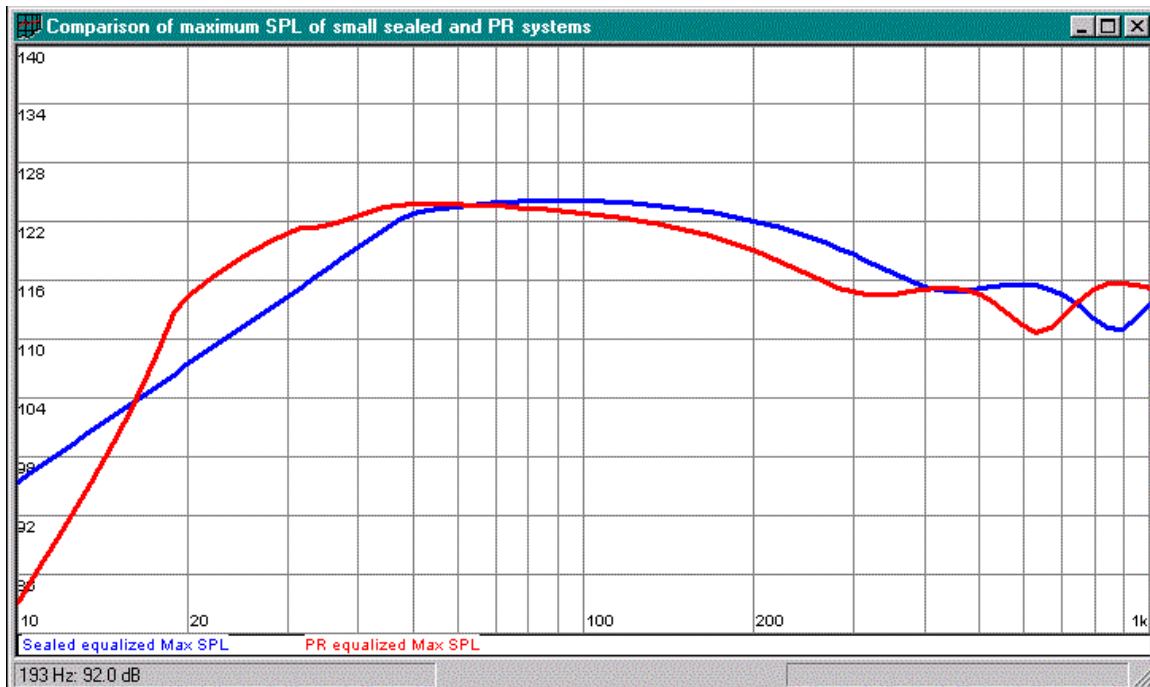


Figure 11 - Comparison of maximum SPL of small sealed and PR systems

As can be seen, the small sealed box has more SPL in the upper midbass region; the smaller box provides additional support for the driver. However, in the frequencies below 70 Hz, the PR system outperforms the sealed box. In fact, between 20 Hz and 33 Hz, the PR system has a 5+ dB advantage in maximum SPL output. And the PR system will have more maximum SPL than the sealed system from 16 Hz to 61 Hz.

There is a tradeoff to equalized systems, however. Because of the equalization typically being of a $Q > 0.707$ filter, there will be a requirement for additional headroom in the amplifier. For example, the $Q=1.91$ EQ used for the PR system has a total voltage gain of 5.91 dB; thus for a nominal 100W delivered in the unequalized passband (~70 Hz and up), one will need ~390W worth of drive ability to use the equalization. Given the relative low-cost availability of large wattage amplifiers (from companies such as Mackie and QSC, or larger used amplifiers from companies like Carver and Hafler), this is often an acceptable tradeoff.

4.9.4 Multiple Shivas

Many systems are designed using multiple drivers. However, calculation of the effective sensitivity and total impedance becomes complicated by the many connection options offered by multiple drivers. Using dual voice coil drivers only increases the confusion. The following table gives the nominal impedance and sensitivity of multiple driver setups.

Number Drivers	Voice Coil Connection	Driver Connection	Impedance, ohms	Efficiency @ 1 W, 1 m	Sensitivity @ 2.83Vrms, 1m
1	Parallel	N/A	4	87.5 dB SPL	90.5 dB SPL
1	Series	N/A	16	87.5 dB SPL	84.5 dB SPL
2	Parallel	Parallel	2	90.5 dB SPL	96.5 dB SPL
2	Parallel	Series	8	90.5 dB SPL	90.5 dB SPL
2	Series	Parallel	8	90.5 dB SPL	90.5 dB SPL
2	Series	Series	32	90.5 dB SPL	84.5 dB SPL
3	Parallel	Series	12	92.3 dB SPL	90.5 dB SPL
3	Series	Parallel	5.3	92.3 dB SPL	94.1 dB SPL
4	Parallel	Parallel	1	93.5 dB SPL	102.5 dB SPL
4	Parallel	Series	16	93.5 dB SPL	90.5 dB SPL
4	Series	Parallel	4	93.5 dB SPL	96.5 dB SPL
4	Series	Series	64	93.5 dB SPL	84.5 dB SPL

Table 9 - Multiple Shiva impedance and sensitivity chart

The effective efficiency and voltage sensitivity gains from running multiple drivers can be calculated as:

Efficiency gain @ 1W, 1m = $10 * \log_{10}(\text{Number Drivers})$

Sensitivity gain @ 2.83Vrms, 1m = $10 * \log_{10}(8\Omega / \text{nominal impedance})$

The net efficiency of the system is the base Shiva efficiency (87.5 dB SPL @ 1W, 1m) plus the efficiency gain for multiple Shivas.

The net sensitivity of the system is the base Shiva efficiency (87.5 dB SPL @ 1W, 1m) plus the efficiency plus the sensitivity gain for the impedance load.

EXAMPLE: assume that 7 Shivas will be used. Each will be wired with voice coils in series, and all units wired in parallel. The nominal impedance is $(16/7) 2.286\Omega$.

Efficiency gain = $10 * \log_{10}(7) = 8.45 \text{ dB SPL}$

Sensitivity Gain = $10 * \log_{10}(8\Omega / 2.286\Omega) = 5.44 \text{ dB SPL}$

Thus the net efficiency and sensitivity of the 7 Shiva system is:

System Efficiency = $87.5 \text{ dB SPL} + 8.45 \text{ dB SPL} = 95.95 \text{ dB SPL @ 1W, 1m.}$

System Sensitivity = $87.5 \text{ dB SPL} + 8.45 \text{ dB SPL} + 5.44 \text{ dB SPL} = 101.39 \text{ dB SPL.}$

Note that wiring for a net impedance higher than 8Ω will result in a reduction in system sensitivity, but will not affect the efficiency of the system.