EQSS™
Equalized Quasi-Sealed System

A METHOD FOR ACHIEVING EXTENDED LOW-FREQUENCY RESPONSE IN A LOUDSPEAKER SYSTEM

ABSTRACT

EQSS™ is a promising technique for achieving extended low-frequency response and increased low-frequency sound pressure output capability in a loudspeaker system. The approach includes a low-frequency driver in a ported box tuned to a sufficiently low frequency so as to result in a frequency response that can be modeled as a second-order response. The resulting driver-box combination is then equalized with a second-order bi-quadratic filter function to achieve the desired frequency response characteristic.

1. Introduction

One of the major challenges in loudspeaker system design is in achieving extended low-frequency performance without large drivers and cabinets. The goal is to achieve a frequency response that extends to low frequencies in or below the 20-50 Hz range. A more difficult challenge is to achieve high output sound pressure levels (SPL) at these same low frequencies, owing to the need to move large amounts of air in order to achieve high sound pressure levels. This goal is made more difficult when this performance must be achieved in a small enclosure, or with small loudspeaker drivers, or both.

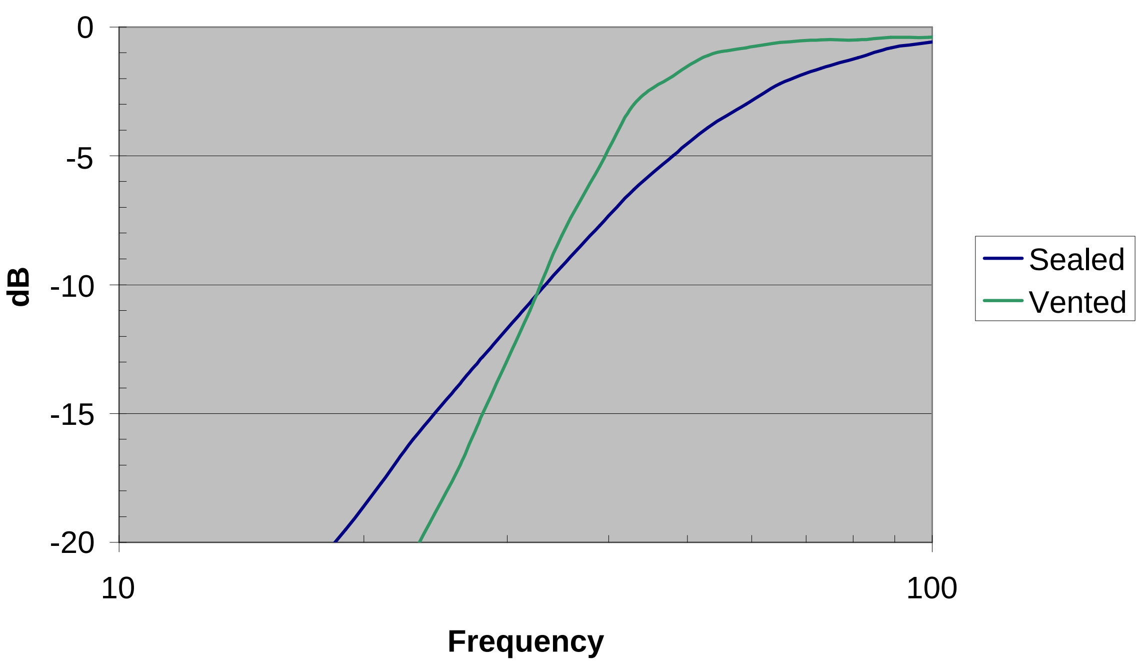
The maximum cone excursion of the driver, in combination with the driver's effective cone area, determines the amount of air that can be moved. This in turn sets a limit on sound levels that can be achieved at low frequencies. The low-frequency SPL limitation is referred to as Excursion-Limited SPL, or ELSPL. The ELSPL of a driver is a function of frequency, and typically decreases at lower frequencies because a correspondingly larger amount of air must be moved at lower frequencies to achieve a given SPL.

Most conventional loudspeaker system designs fall into one of two broad categories: sealed systems or ported systems. Sealed systems, often called closed-box systems or acoustic suspension systems, provide a second-order high-pass frequency response that limits their low-frequency extension. They suffer from higher low-frequency –3 dB cutoff frequencies ($f3$) and lower ELSPL as compared to ported systems. The low frequency cutoff frequency of a sealed system can be reduced, but at the expense of a much larger box. Alternatively, the *f*3 of such a system may be reduced by employing a woofer with a heavier cone which reduces the resonant frequency of the system. Unfortunately, employing a heavier cone usually results in much reduced efficiency. In either case, however, low-frequency ELSPL is not increased.

Ported systems, also known as vented systems, add a port to the box in which the driver is mounted, forming a Helmholtz resonator. When properly designed, the box-port Helmholtz resonance produces a lower *f*3 and also produces a higher ELSPL at low frequencies. In such systems, the box-port Helmholtz resonant frequency is referred to as *f*b. These systems provide a fourth-order high pass frequency response. As frequency is reduced from higher frequencies down to *f*3 and then to frequencies below *f*3, the frequency response begins to fall off very sharply, at a rate approaching 24 dB/octave. The steep roll-off typically begins at frequencies below the box tuning frequency *f*b. The steep low frequency roll-off tends to cause group delay distortion and poor transient response. Although ported systems provide increased ELSPL at frequencies above *f*3, the ELSPL of ported systems falls off severely at frequencies below *f*b, providing virtually no useful output at such frequencies. Ported systems actually produce *less* ELSPL than that of a comparable sealed system at frequencies below *f*b of the ported system.

Figure 1 shows typical frequency response curves for ported and sealed systems.

Figure 1: Sealed & Vented Responses



There are many commercial examples of low-frequency sealed systems designed for extended low-frequency performance in the form of subwoofers. These are often merely brute-force sealed systems that employ a special driver with very large cone mass and very large cone excursion. Such designs result in very low efficiency and require extremely high drive power. The very high cone mass also compromises transient response.

A small number of sealed systems employ equalization in order to achieve an extended low frequency response with a reduced f_3. This approach does not suffer from the approaches mentioned above wherein larger cabinets or reduced electrical efficiency is required. In these systems, equalization is often done with an active filter placed in the signal path prior to the power amplifier that drives the loudspeaker. These equalizers typically provide a bi-quadratic filter function that includes a pair of zeros and a pair of poles. The pair of zeros is typically placed at or near the same frequency as the pair of poles produced by the un-equalized sealed system. The pair of bi-quadratic poles is placed at a lower frequency corresponding to the desired equalized f_3 of the system. Such an equalizer is also known as a Linkwitz Transform.

The approach using a Linkwitz Transform with a sealed system is an example of what is referred to here as an Equalized Sealed System (ESS). It is very effective at improving the frequency response of the sealed system loudspeaker. However, it does nothing to improve the low-frequency ELSPL. In order to have an ELSPL commensurate with the extended low frequency response afforded by the ESS technique, these systems typically must employ a large driver with a very large excursion capability. Such systems may typically employ equalization to move the system f_3 down by about one octave. This corresponds roughly to 12 dB of equalization, which in turn corresponds to an increased power of 16 times at the f_3 of the equalized system. This is a direct consequence of the greatly reduced efficiency of a sealed system at frequencies below its un-equalized f_3. As a result, large power amplifiers are often required for use with such systems.

The Bag End ELF™ system is a commercial example of a different equalized sealed system. This system comprises essentially a double integrator equalizer placed in the input signal path of a sealed system. This is an alternative to the Linkwitz Transform. It has all of the same shortcomings and does nothing to improve ELSPL.

Ported systems can be equalized, but in practice they virtually never are equalized. This is partly due to the greater difficulty of accurately equalizing a fourth-order system and the larger amount of correction required. More important is the fact that it makes little sense to equalize a conventional ported system to achieve a lower f_3. This is so because the f_3 of a conventional ported system usually lies near the box tuning frequency, and the ELSPL drops off severely at frequencies below f_b. For these reasons, it has usually been impractical to equalize ported systems.

One example of combining an “equalizer” with a ported system is the 6th order Chebeychev vented alignment originally described by Theile. This approach provides a small amount of bass extension at the expense of a much worse transient response. The active filter in this approach is essentially a second-order high-pass filter, unlike the low-pass equalizer used in the equalized sealed systems described above. This approach also does little for low-frequency SPL capability. Such "electronically assisted vented designs" have also been discussed by Vance Dickason in his "*Loudspeaker Design Cookbook*", with particular focus on such sixth-order designs proposed by Robert Bullock in his article that appeared in *Speaker Builder* in 1/82.

Conventional approaches for achieving extended low-frequency performance are sub-optimal in one or more of the performance metrics that include $f3$, ELSPL, efficiency, box size and transient response. All of the above-mentioned approaches fail to realize the combined benefits of the EQSS™ approach.

2. The Basic Idea

EQSS™ addresses the limitations of conventional approaches for providing extended low-frequency response and SPL from loudspeaker systems. Here is how it works. A ported system can be made to act much like a sealed system in both frequency response shape and roll-off slope over an extended band of low frequencies when the box tuning frequency is chosen to be unusually low. By this we mean substantially lower than the fb commonly used with a given driver-box combination. It also turns out that the low-frequency SPL capability of such an unusual ported system is greatly improved compared to that of a similar sealed system. This is true even at frequencies well below the 3 dB frequency response point of the "low-tuned" ported system. We refer to such a ported system that has a frequency response similar to that of a sealed system as a Quasi Sealed System (QSS). Note that this is not the same as what is sometimes referred to as an EBS (Extended Bass Shelf) alignment.

Figure 2: Sealed, Vented & QSS Responses

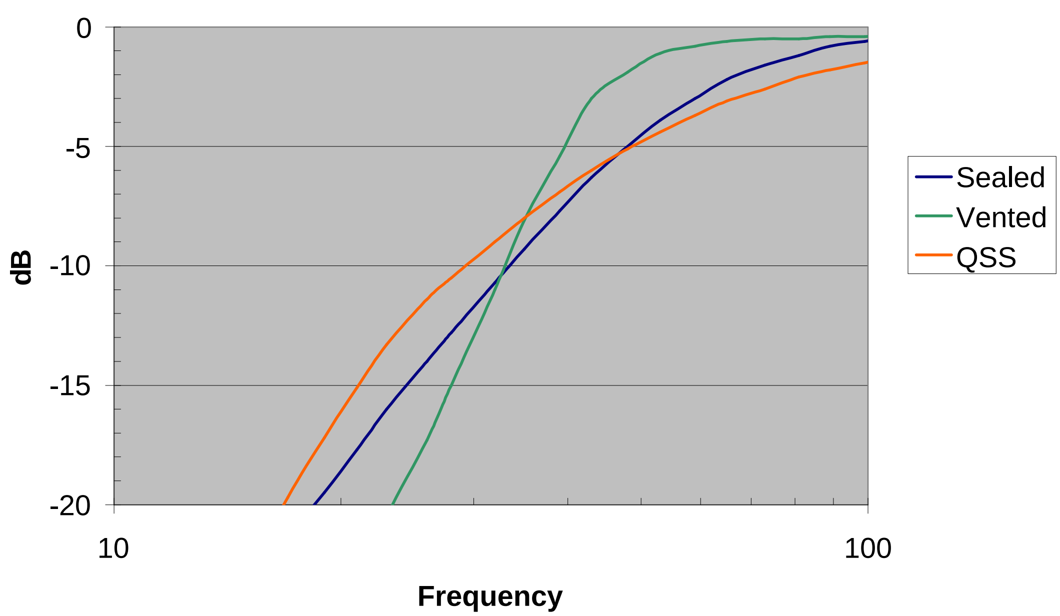


Figure 2 shows the frequency responses of the previous sealed and ported systems with a third response added in orange corresponding to that of a Quasi Sealed System.

Let's also define a Virtual Sealed System (VSS) as a sealed system design whose box volume and driver parameters have been manipulated so that its frequency response accurately models that of a Quasi Sealed System over the frequency range of interest.

These observations are the basis for the Equalized Quasi Sealed System (EQSS™) described here. The EQSS™ approach includes a low-frequency driver in a ported box with an unconventionally low box tuning frequency f_b, and an equalizer that corrects the resulting frequency response to become a desired frequency response that extends to lower frequencies than would be the case without the equalization.

In the EQSS™ approach, we set the box tuning frequency such that the frequency response of the driver-box combination at the box tuning frequency is substantially below the reference response level (e.g., -6 to –12 dB). The resulting frequency response then approximates a second order response down to frequencies at least one-half octave below the box tuning frequency. The combined driver, box, port and tuning frequency then comprise a Quasi Sealed System (QSS).

The required equalization can be accomplished by providing a bi-quadratic filter function providing two poles and two zeros in its frequency response. This equalizer is commonly known as the Linkwitz Transform mentioned above. We compute the equalizer parameters in accordance with proper equalization of the Virtual Sealed System whose frequency response accurately models that of the Quasi Sealed System. This approach is therefore referred to as an Equalized Quasi Sealed System (EQSS™).

3. How It Works

Figure 3 is a block diagram of a loudspeaker system employing the EQSS™ technique. The input signal passes through an equalizer, which drives the power amplifier, which in turn drives the loudspeaker. The low-frequency driver is housed in a vented box with a tuning frequency that makes it a Quasi Sealed System (QSS).

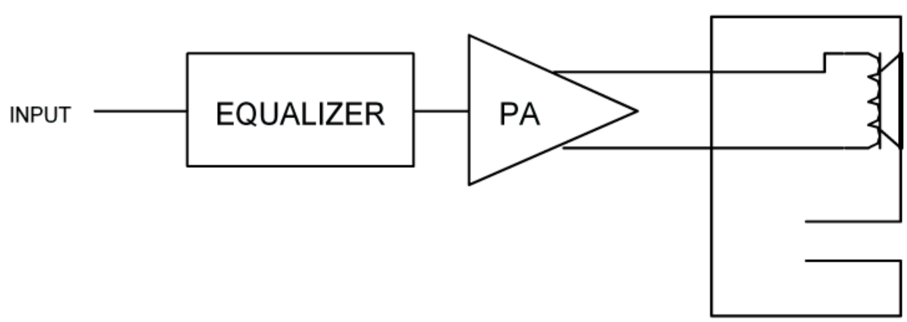


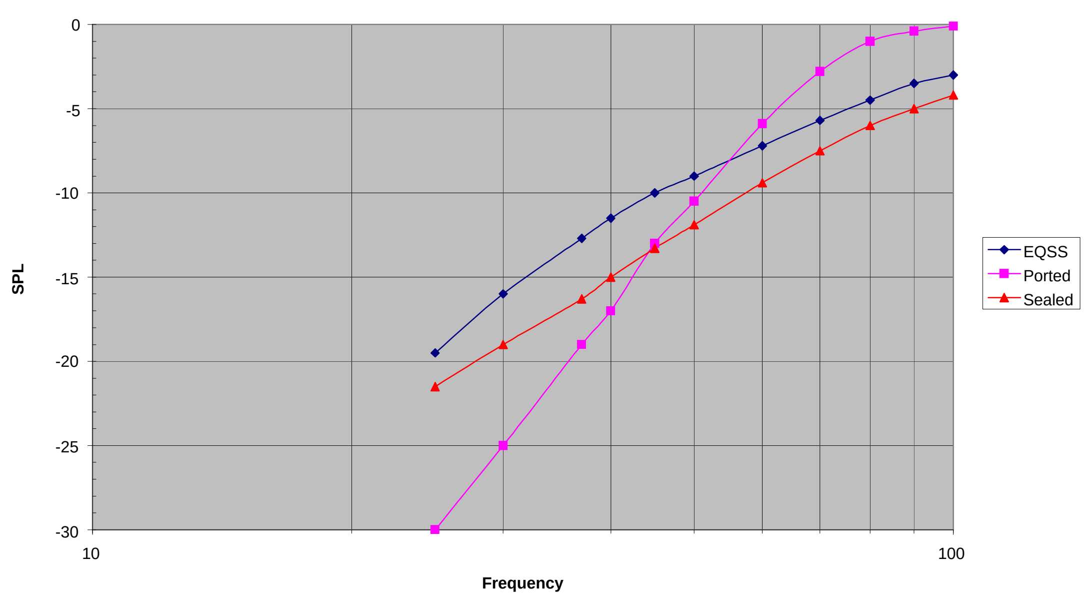
Figure 3: An EQSS™ Loudspeaker System

Figure 4 illustrates the frequency responses of three different speaker systems, all without equalization. The vertical axis indicates relative sound pressure level (SPL), while the horizontal axis indicates frequency in Hertz. All three systems employ the same 5.25-inch low-frequency driver in the same box volume. The driver is characterized by the usual Thiele-Small parameters. The driver in the example here has the following Thiele-Small parameters:

Vas	15.5 L
*f*s	55 Hz
Qts	0.35
Xmax	2.5 mm
D	11.4 cm
Vbox	9.0 L

The first system, whose frequency response is denoted by triangles in the graph, is a conventional sealed-box system built with this driver in the 9-Liter box. It has a second-order frequency response roll-off with decreasing frequency at a rate of approximately 12 dB per octave. Its frequency response is down 3 dB at approximately 110 Hz, relative to a reference level of 0 dB at higher frequencies. At a much lower frequency of 35 Hz, its response is down approximately 16 dB from the reference level.

Figure 4: Frequency Responses of three Systems



The second system, whose frequency response is denoted by squares, is a ported system built with this driver. It includes a port that tunes the 9-Liter box to a frequency f_b of approximately 65 Hz. The ported system has an extended low-frequency 3 dB response as compared to the sealed system just described. Its response is down 3 dB at approximately 68 Hz. However, its response at the much lower frequency of 35 Hz is down about 19 dB, having a weaker response at this lower frequency than the sealed system. It has a fourth-order frequency response roll-off with decreasing frequency at a rate approaching 24 dB per octave. Such is the frequency response tradeoff between sealed and ported systems.

The third system, whose frequency response is denoted by diamonds, is a system based on the EQSS™ technique. It is a Quasi Sealed System (QSS) implemented with the same driver in the same box volume as the sealed system described above, but with a port added that causes the box to be tuned to a frequency f_b of approximately 37 Hz.

The QSS arrangement has a second-order roll-off like that of the sealed system for most of the frequency range, but it has increased low-frequency response as compared to the sealed system. Its frequency response is down 3 dB at 100 Hz as compared to 110 Hz for the sealed system.

At the much lower frequency of 35 Hz, its frequency response is down only 13 dB, as compared to the conventional sealed system whose response is down 16 dB at the same frequency. The QSS system thus exhibits a 3 dB increase in efficiency at 35 Hz as compared with the sealed system.

Although the QSS system is ported, it can be seen that its frequency response is much more like that of a sealed system than a ported system. It is for this reason that it is referred to as a Quasi Sealed System. Note also that the QSS response is fully 6 dB stronger than the response of the ported system at 35 Hz.

The frequency response of the QSS system is accurately modeled by a so-called Virtual Sealed System (VSS) consisting of a 12-Liter sealed box and a “virtual” 5.25-inch driver with the following Thiele-Small parameters:

Vas	20 L
f_s	43 Hz
Qts	0.33
Vbox	12.0 L

The virtual sealed system is characterized by a critical frequency of 70 Hz, a 3 dB frequency f_3 of 98 Hz, and a Q of 0.54.

We can see that the Quasi Sealed System, although ported, acts like a sealed system, but with increased efficiency at low frequencies. It should also be clear that the frequency response of the QSS may be equalized in the same way as the Virtual Sealed System could be equalized, using the same bi-quadratic filter function. This is so because their frequency responses are essentially the same. If the response of the

Quasi Sealed System is equalized to become the more desirable one, the EQSS™ system will be the result.

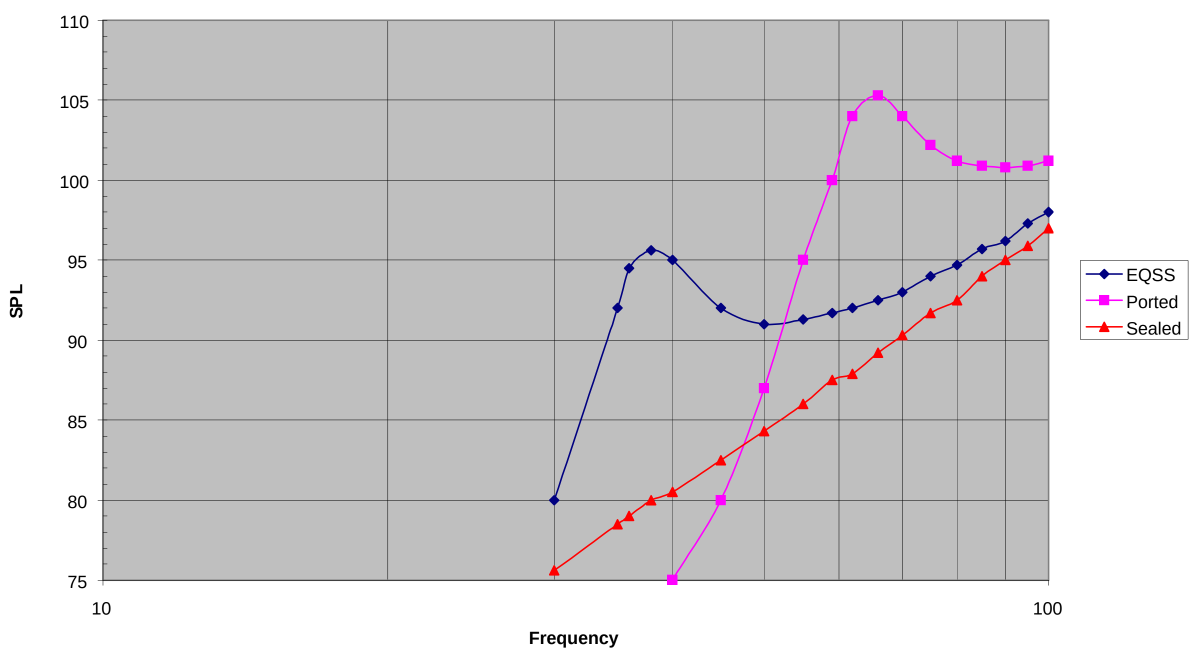
The accuracy of how well the Quasi Sealed System is modeled by the Virtual Sealed system is of particular interest. While the QSS acts like a sealed system with a 12 dB/octave roll-off down to a certain frequency, at lower frequencies it will ultimately assume the 24 dB/octave slope of the ported system that it really is. Ultimately, the response of the QSS will fall below that of the VSS at low frequencies for this reason.

In the example here, the error of the model reaches 1 dB at a frequency of 26 Hz, or about 70% of the box tuning frequency of 37 Hz. The error reaches 3 dB at a frequency of 22 Hz, or about 59% of fb. We refer to this 3 dB error frequency as the Model Bandwidth. The fact that the model bandwidth extends for the better part of an octave below the box tuning frequency is encouraging.

4. Achieving High SPL at Low Frequencies

Figure 5 illustrates the Excursion-Limited SPL (ELSPL) of the same three speaker systems discussed above in connection with Figure 4. The vertical axis indicates Sound Pressure Level (SPL), while the horizontal axis indicates frequency in Hertz. The maximum undistorted SPL that can be reproduced by a loudspeaker at low frequencies is limited by the distance that the loudspeaker's cone can move in and out.

Figure 5: Excursion Limited SPL of three Systems



This distance is referred to as the loudspeaker's excursion. So-called Xmax is conventionally defined as the maximum linear movement in one direction from the resting position of the cone. In order to reproduce sound at low frequencies at high levels, a loudspeaker must move a large amount of air. The loudspeaker's ability to move air is called its displacement. A loudspeaker's displacement is proportional to the product of its effective cone area and its excursion.

This is why, for a loudspeaker of a given diameter, its maximum low-frequency SPL is limited by its maximum excursion. Because the amount of air that must be moved for a given SPL is a function of frequency, the ELSPL for a given loudspeaker is a function of frequency, as shown in *Figure 5*. It should be noted that the SPL values in *Figure 5* are obtained at whatever electrical drive level is necessary to cause the loudspeaker driver to operate at its maximum excursion (Xmax) at the given frequency.

The first system, whose ELSPL is denoted by triangles in the graph, is the conventional sealed-box system. As can be seen from *Figure 5*, it is capable of an ELSPL of at least 87 dB SPL down to a frequency of 60 Hz. However, at the much lower frequency of 35 Hz, it is capable of an ELSPL of only 78 dB SPL. This greatly reduced SPL capability at low frequencies is typical of sealed systems.

The second system, whose ELSPL is denoted by squares, is the conventional ported system. As can be seen from *Figure 5*, the ported system provides substantially larger ELSPL over the mid and upper bass range than the sealed system. This is due to the action of the port, which loads the loudspeaker driver and produces substantial SPL output at frequencies in the vicinity of the box tuning frequency *f*3. Notice the peak in the ELSPL curve of 105 dB SPL at the box tuning frequency of 65 Hz.

Now notice the "saddle" in the ELSPL curve centered about 90 Hz. Here we see a local minima in the ELSPL as a function of frequency. This local minimum ELSPL is about 101 dB SPL, and is what we will refer to as the maximum usable ELSPL of the system. Any ELSPL above this amount is gravy that may or may not be available depending on frequency. Finally, the last frequency of interest is at approximately 35 Hz, where the ELSPL has dropped from the peak value down to the same value as the local minima (saddle) value. This is the lowest frequency down to which the maximum usable SPL described above is achievable. As can be seen from *Figure 5*, the ported system is capable of an ELSPL of at least 101 dB down to a frequency of 60 Hz. This is fully 14 dB of increased SPL output capability as compared to the sealed system at a frequency of 60 Hz.

If system reproduction down to only 60 Hz were the objective, the ported system would be entirely satisfactory. However, one objective of the EQSS™ technique is to obtain both frequency response and a useful amount of output down to lower frequencies. One unfortunate characteristic of conventional ported systems is that their ELSPL drops precipitously at frequencies below the box tuning frequency *f*3. This can be seen in *Figure 5*. At the very low frequency of 35 Hz, the ELSPL of the ported system is actually far worse than that of the sealed system, being only approximately 70 dB SPL at 35 Hz. Thus, the ported system is fully 8 dB less capable of ELSPL than the sealed system at 35 Hz.

Based on these observations, it is clear that ported systems are not satisfactory for reproducing deep bass at frequencies below the box tuning frequency $f3$. Moreover, conventional ported systems with very low box tuning frequencies are generally difficult to implement in small boxes with small drivers.

The third system in *Figure 5*, whose ELSPL is denoted by diamonds, is a QSS arrangement based on the EQSS™ technique. It is identical to the one whose frequency response was shown in *Figure 4*. It can be seen from *Figure 5* that the Quasi Sealed System (QSS) is capable of an ELSPL of at least 92 dB SPL down to frequencies as low as 60 Hz. This is 5 dB better than the sealed system over the same frequency range. It is less than the local101 dB ELSPL capability of the ported system at 60 Hz, but the larger ELSPL of the ported system is not in a frequency range where it is really needed when viewed in the context of the objectives here. Now we begin to see the engineering tradeoff made possible by the EQSS™ technique.

Referring to the ELSPL capability of the QSS, note that the ELSPL has a saddle at 53 Hz where the ELSPL drops to a local minima of 91 dB. This again is the maximum usable ELSPL of the QSS. The ELSPL rises to 95.7 dB at 39 Hz, and then falls to 91 dB at 35 Hz. Thus, at frequencies ranging down to as low as 35 Hz, it is evident that the Quasi Sealed System is capable of an ELSPL of at least 91 dB SPL over this entire frequency range. This is 13 dB better than the 78 dB ELSPL capability of the sealed system at 35 Hz. It is a remarkable 21 dB better than the 70 dB ELSPL capability of the ported system at the same 35 Hz frequency.

5. The Equalizer

Figure 6 is a schematic diagram of an equalizer circuit that is suitable for use in implementing the EQSS™ technique. The equalizer requires only one operational amplifier. Such an equalizer may take many forms, and can be designed by widely available software programs. The combination of passive components and the operational amplifier in *Figure 6* implements a bi-quadratic active filter function sometimes referred to as a *Linkwitz Transform*.

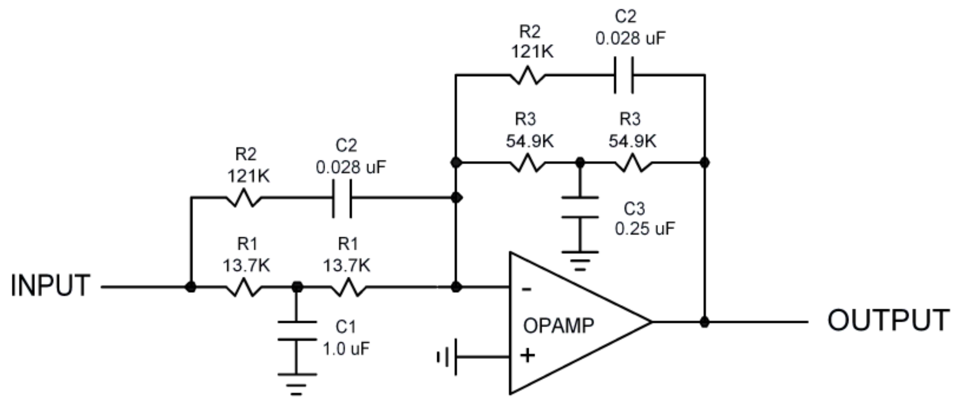
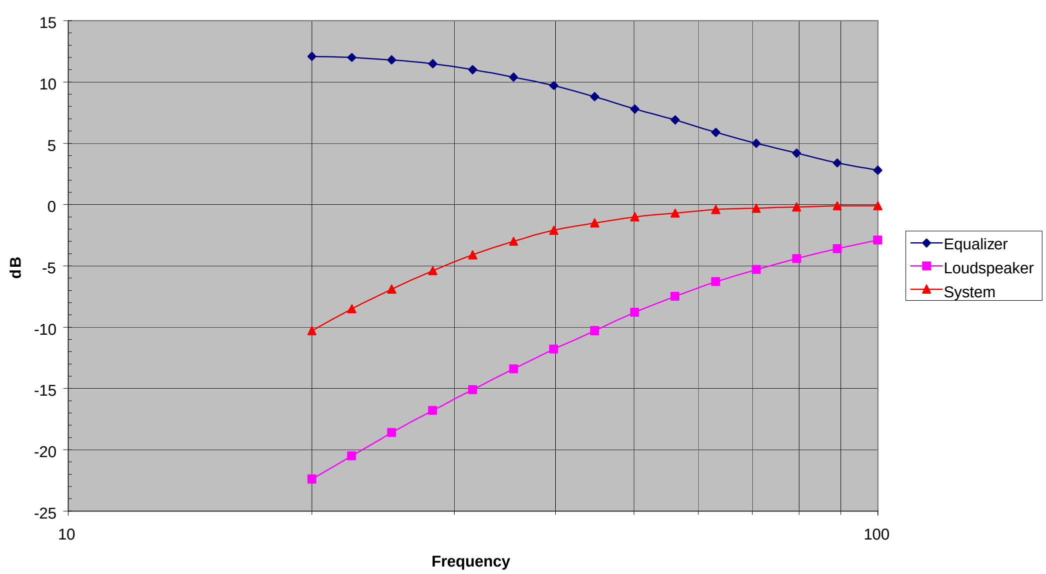


Figure 6: An Equalizer for Implementing EQSS ™

Figure 7 is a frequency response graph showing the un-equalized response of a Quasi Sealed System represented by squares, the frequency response of the equalizer represented by diamonds, and the total frequency response of the complete EQSS™ arrangement represented by triangles.

Figure 7: Frequency Responses



The response of the QSS falls with decreasing frequency, being down 3 dB at approximately 90 Hz. The response of the equalizer, on the other hand, rises with decreasing frequency, being up approximately 3 dB at 90 Hz. Similarly, at 35 Hz the response of the QSS is down 14 dB while the response of the equalizer is up 11 dB. The combination of the equalizer and the QSS provides a system response with extended low frequency response and a –3 dB frequency of approximately 35 Hz.

As mentioned above, the example 5.25-inch driver in the Quasi Sealed System can reach an excursion-limited SPL of 91 dB down to 35 Hz. The response of the equalizer is up 11 dB at this frequency, and the reference efficiency of the driver is 90.3 dB. This means that at 35 Hz, the net efficiency is actually 79.3 dB. Keep in mind that in any ordinary system, its efficiency is down 3 dB from its reference efficiency at its 3 dB down frequency. Returning to the example, we see that in order to achieve the excursion-limited SPL at 35 Hz, we must provide the speaker with 91 - 79.3 = 11.7 dBW, or about 15 Watts.

This EQSS™ design example using a 5.25-inch driver is the design used in the *Athena* active loudspeaker system described elsewhere on this web site. In that system, four 5.25-inch drivers are employed in each enclosure. Since each doubling of the number of drivers increases efficiency by 3 dB, that system achieves a mid-band sensitivity of 96 dB SPL/one watt.

The use of four drivers also increases maximum SPL capability. Since each doubling of the number of drivers increases SPL by 6 dB, that system achieves an ELSPL of 91 + 12 = 103 dB SPL down to 35 Hz. Note that a stereo pair of the Athenas can achieve an ELSPL of an additional 6 dB, for a total of 109 dB SPL at 35 Hz. This is remarkable for a system composed only of small 5.25-inch woofers. For most listening applications, such a system does not need a subwoofer.

The performance of the EQSS design employing four 5.25-inch drivers is summarized as follows:

• 3-dB frequency $f3$	35	Hz
• 6-dB frequency $f6$	27	Hz
• Mid-bass efficiency	96	dB SPL
• Efficiency at 35 Hz	85	dB SPL
• Amplifier Power (MB)	5	Watts
• Amplifier Power (LF)	60	Watts
• SPL at 35 Hz	103	dB SPL
• Xmax (each driver)	2.5	mm

Amplifier Power is the required power to achieve 103 dB SPL at Mid-bass frequencies (MB) or at 35 Hz (LF).

6. Subwoofers

Figure 8 is a block diagram illustrating the use of the EQSS™ technique in connection with a subwoofer loudspeaker system. In this arrangement the input signal passes through a subwoofer crossover before entering the EQSS™ equalizer. In most applications, the subwoofer crossover, the equalizer and the power amplifier would be implemented together in the “plate amplifier”. The EQSS™ technique is especially advantageous for implementing subwoofers because subwoofers must be able to produce low frequencies faithfully at high levels, but often with a box of modest size and volume.

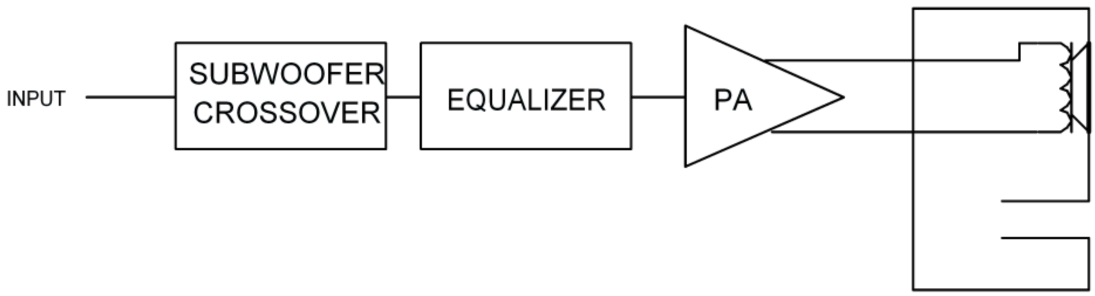


Figure 8: An EQSS™ Subwoofer Loudspeaker System

The EQSS™ technology is equally advantageous in small-box and conventional-sized subwoofers, but here we will focus on a small-box subwoofer implemented in a one-cubic-foot enclosure.

A small-box EQSS™ subwoofer can be implemented with a 10-inch woofer (Dayton II) in a one cubic foot box having the following Thiele-Small and tuning parameters:

Vas	78 L
*f*s	34 Hz
Qts	0.32
Qes	0.33
Eff.	91.5 dB SPL
Xmax	5.5 mm
D	21.5 cm
Vbox	28.2 L
*f*b	30 Hz

This combination of driver, box and port forms a Quasi Sealed System (QSS) whose frequency response is accurately modeled by a Virtual Sealed System (VSS) comprising a box with a volume of 25 Liters and a virtual driver with the following Thiele-Small parameters:

Vas	78 L
*f*s	30 Hz
Qts	0.34
Vbox	25 L

The model is accurate to within 1 dB down to frequencies as low as 18Hz. The Model Bandwidth, where the error reaches 3 dB, is 13.6 Hz. This is approximately 45 percent of the box tuning frequency of 30 Hz.

The Quasi Sealed System for the subwoofer is capable of producing 105 dB SPL or more down to frequencies as low as 28 Hz. This is very impressive when one realizes that the driver has an Xmax of only 5.5 mm. The un-equalized QSS has a frequency response that is down 3 dB at 60 Hz. With a proper bi-quadratic equalizer providing a maximum boost of 12.3 dB, the frequency response of the complete EQSS™ arrangement is down 3 dB at 30 Hz with a system Q of 0.7.

Performance is summarized as follows:

- 3-dB frequency f_3 30 Hz
- 6-dB frequency f_6 23 Hz
- Mid-bass efficiency 91.5 dB SPL
- Efficiency at 30 Hz 79.3 dB SPL
- SPL at 30 Hz 105 dB SPL
- Xmax 5.5 mm

7. Full Range Systems

Figure 9 is a block diagram illustrating the use of the EQSS™ technique in connection with a full-range, three-way active loudspeaker system that employs an active crossover and multiple power amplifiers. The high frequency (HF) output of the crossover is fed to a power amplifier, and then to the tweeter as in a conventional active speaker system. Similarly, the midrange frequency (MF) output of the crossover is directed to a second power amplifier, and then to the midrange loudspeaker. The LF output of the crossover is fed to the EQSS™ equalizer and then to the third power amplifier, and finally to the woofer. The EQSS™ equalizer can be designed into the active crossover module.

The *Athena* active loudspeaker system described elsewhere on this web site is an example of a full range active system that employs the EQSS™ technology. The Athena is a three-way system that incorporates four 5.25-inch woofers in an EQSS™ arrangement. The woofers are grouped into two pairs. Each pair is driven by a 125-Watt Class-AB MOSFET power amplifier. A three-inch midrange and a one-inch silk dome tweeter are also each driven by a 125 Watt power amplifier.

The EQSS™ technique allows good bass extension and excellent low-frequency SPL to be achieved with the four 5.25-inch drivers The small drivers in turn allow the use of a mini-tower that is only 7 inches wide. The footprint of the *Athena* is only 37 X 7 X 17 inches (HWD). The *Athena* is down 3 dB at 35 Hz and is capable of 103 dB SPL down to 35 Hz.

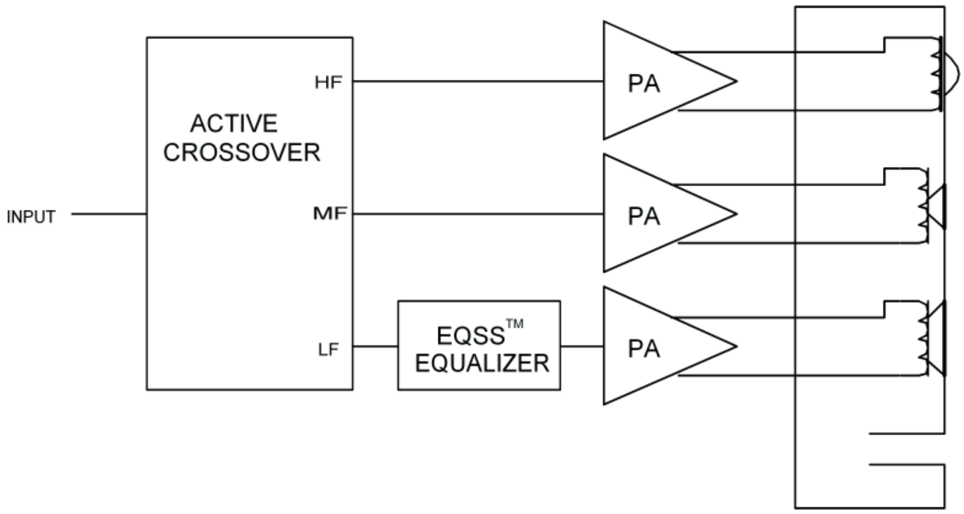


Figure 9: A Full-Range Loudspeaker System Using EQSS™ with Active Crossovers

Figure 10 is a block diagram illustrating the use of the EQSS™ technique in connection with a largely conventional full-range loudspeaker system that employs a passive crossover and a single power amplifier. The passive crossover is located inside the loudspeaker enclosure, and the loudspeaker is powered with a conventional power amplifier that would normally be a part of the rest of the entertainment system. Here the EQSS™ equalizer is placed between the line-level signal source (typically a preamplifier) and the power amplifier. The passive speaker system is conventional in every way except that it includes a ported enclosure that has been designed in conformance with the EQSS™ technique so as to yield a Quasi Sealed System that can be properly equalized by the EQSS™ equalizer.

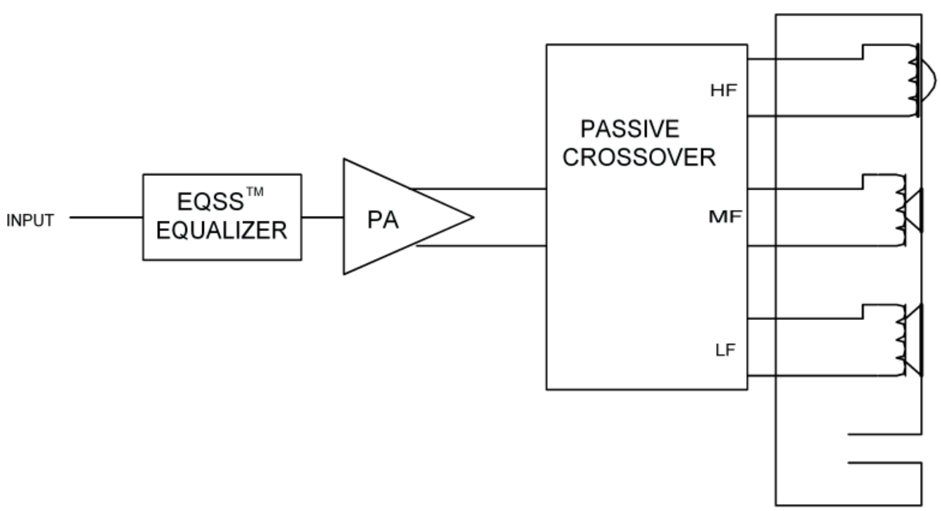


Figure 10: A Full-Range Loudspeaker System Using EQSS™ with Passive Crossovers

8. Other Applications

The EQSS™ technique can also be used to advantage in automobile subwoofer systems, where the advantages of extended low frequency response, high SPL capability at low frequencies, and high efficiency afforded by EQSS™ are all of great value. Larger automobile subwoofer systems with a long box dimension of 24 inches or more especially benefit from the EQSS™ technique because of the ease with which they can accommodate a long port of adequate diameter, providing for low box tuning frequencies.

Another application of the EQSS™ technique is in Home Theater satellite-subwoofer speaker systems. The EQSS™ technique is especially advantageous to such an application because the small satellite speakers in such systems often have very poor low frequency response. This is a result of their very small size, and requires the subwoofer to operate at frequencies higher than normal for subwoofers (e.g., upwards of 200 Hz). An EQSS™ subwoofer has improved high frequency response in comparison with conventional subwoofers because the loudspeaker driver of an EQSS™ subwoofer does not have to be optimized for a subwoofer application, meaning that its high-frequency response need not be compromised by use of, for example, a heavy cone with large excursion capability.

The EQSS™ technique also lends itself readily to distributed subwoofer systems. In many situations, a multiplicity of small subwoofers can produce a better low end than a single large subwoofer, owing to room placement and standing wave issues. Recall the earlier example of the 5.25-inch woofer in a ported 9-Liter box tuned to 37 Hz. The system was flat to 35 Hz (-3 dB) and was capable of an SPL of 91 dB down to 35 Hz. This could be a very decent, very small, subwoofer. One could distribute four of these little boxes around the room, achieving a total 103 dB SPL in the room down to 35 Hz (not including room gain).

9. Design Procedure

Here we summarize the EQSS™ design procedure and describe the example software tools that have been used in the design illustrations above. As with any design synthesis, there are many different starting assumptions that can be made, and many different ways of iterating and optimizing the design.

One of the very big advantages of the EQSS™ technique is that it allows great freedom in picking a driver. Indeed, because equalization is fundamental to the EQSS™ technique, the issue of frequency response is divorced from matters of box size, tuning frequency and achievable ELSPL. For this reason, in the simple design procedure we describe here, we assume that the designer picks the driver and goes from there.

The chosen driver's parameters and the target box volume are first analyzed for performance as a function of box tuning frequency. The main performance characteristic of interest is the maximum excursion-limited SPL (ELSPL) as a function of frequency. This design space exploration was carried out by using the ***ported.xls*** spreadsheet developed by Brian Steele (available at www.diysubwoofers.org/port/). This will result in a Quasi Sealed System (QSS) with the desired large-signal performance. The details of its frequency response will largely be ignored at this point.

The next step is to create a Virtual Sealed System (VSS) whose frequency response is essentially the same as that of the QSS down to frequencies at least a half-octave below the box tuning frequency. A very handy feature of the ***ported.xls*** spreadsheet is that it allows one to compare two designs at the same time. These two designs can use different sets of driver parameters and different box sizes and tunings, including sealed.

The VSS is created by designing a sealed system in the ***ported.xls*** spreadsheet in such a way that it has the same frequency response as the QSS. A very good starting point is to use the same driver parameters and box volume as the QSS, but with a sealed box. The driver used for the VSS will then have its parameters altered to become a "virtual" driver that produces the desired matching frequency response. In most cases, alteration of fs and QES of the driver will produce a very good match. It is also entirely acceptable to alter the box volume of the VSS design to achieve the goal. It is merely a virtual system whose characteristics that led to the matching response will be used for the design of the EQSS™ equalizer. With a good match, the VSS and QSS frequency responses will be within about 1 dB of each other down to frequencies at least one-half octave below the box tuning frequency of the QSS.

Remember, we don't care about the efficiency and maximum SPL capability of the VSS. All we seek is a sealed system whose frequency response is a replica of that of the QSS.

We next use True Audio's *Linkwitz Transform Design Spreadsheet* to design the EQSS™ equalizer. This spreadsheet, created by John Murphy, can be found at www.trueaudio.com under Tech Topic number 13. The driver parameters and box volume of the VSS are plugged into the Driver and Box design page of the spreadsheet (one of the last pages of the spreadsheet). The spreadsheet calculations then yield values of $f$sc, Qtc, and f3 for the Virtual Sealed System. It is this system that will be equalized to achieve the desired frequency response of the EQSS™ system.

The EQSS™ equalizer is then designed by going to the equalizer design page of the spreadsheet. $f$sc of the starting system (the VSS) is entered as f(0), and Qtc is entered as Q(0). The desired characteristic frequency and Q of the EQSS™ target system are then entered. The desired value of one of the capacitors in the equalizer design is also entered. The spreadsheet calculations then yield the remaining component values for use in the equalizer. The spreadsheet also provides a plot of the final system frequency response and the equalizer frequency response employed to achieve that.

10. Passive Radiators and Distributed Ports

Figure 11 is an illustration of a loudspeaker system that implements the EQSS™ technique by use of a passive radiator in place of the port. This substitution is advantageous when the box tuning frequency fb and box volume Vb are such that the required length of the port is impractically long. The substitution of a passive radiator, sometimes known as a drone cone, with appropriately specified moving mass and compliance, can yield the desired box tuning frequency in a smaller occupied space, while retaining all of the advantages of the EQSS™ technique.

The design procedures and software for passive radiator systems is different and will not be covered here. However, all of the principles and approaches of the EQSS™ technique are equally applicable to passive radiator systems. The concept of building a passive radiator system that turns out to be a Quasi Sealed System in behavior, and then of emulating it with a Virtual Sealed System still applies directly. A vented system is much like a passive radiator system with infinite compliance in the limit. As the compliance of the passive radiator is introduced, minor changes in the frequency response and excursion characteristics develop, mainly at frequencies below the box tuning frequency.

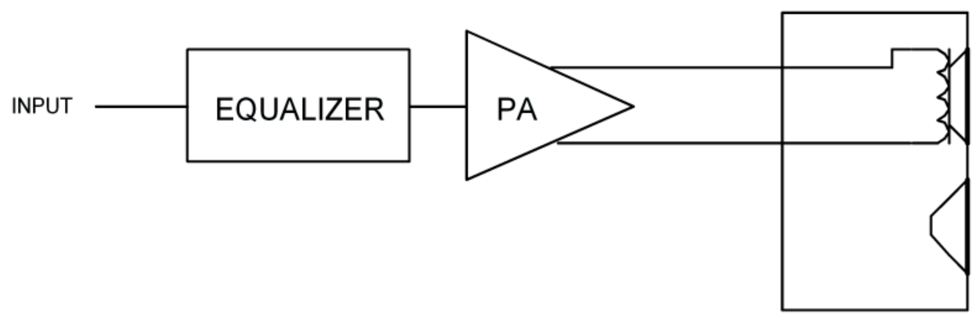


Figure 11: An EQSS™ Arrangement Employing A Passive Radiator

Passive radiators act almost exactly as a port at frequencies down to the box tuning frequency, but they do tend to cause a steeper low-frequency roll-off than a vented system. This is due to the fact that the passive radiator's own resonance below the pass-band causes a notch in the overall frequency response.

The use of flexible distributed ports is an alternative to passive radiators that is especially useful in small enclosures where a conventional port would be too long. A distributed port arrangement consists of a plurality of small ports, typically implemented with flexible plastic tubing so that they can be bent in smooth turns so as to fit in a confined space. Although they can be bundled into a traditional round cross-section, they can also be bundled into a rectangular cross-section, like a slot, or even physically distributed as individual mini ports across a surface of the enclosure. They can even encircle the woofer driver itself.

A conventional 3-inch diameter port can be replaced by sixteen ¾-inch ID tubes. This will result in the same cross-sectional area. The fluid dynamics of multiple small-diameter ports also provide for less turbulent air flow and less port chuffing as a result. The long small-diameter cross-section of the tubes also acts as a better filter to mid-band frequencies originating in the cabinet, reducing their ability to escape through the port.

11. Efficiency

The efficiency of the EQSS subwoofer described above is best evaluated by comparing its performance to that of a typical sealed subwoofer system in a box of the same size. Here we use a Dayton 10-inch Titanic I driver for the comparison. It has an Xmax of 15 mm and an efficiency of 85.7 dB SPL @ 1 Watt/1 Meter. We have the following characteristics for the sealed subwoofer system:

Vas	54 L
f_s	28 Hz
Qts	0.43
Qes	0.48
Xmax	15 mm
D	21.5 cm
Efficiency	85.7 dB SPL
Vbox	28.2 L
f_3	46 Hz
f_6	35 Hz
Q	0.74
ELSPL	109 dB @ 46 Hz
ELSPL	102 dB @ 30 Hz

The driver of the EQSS™ subwoofer example of Figure 8 has a sensitivity of 91.5 dB SPL @ 1 Watt/1 Meter, fully 6 db more efficient than the conventional subwoofer. This corresponds to a factor of four in required driving power to reach a given SPL at upper bass frequencies. This means that the EQSS™ subwoofer can reach 105 dB SPL with less than 30 Watts of electrical driving power from the power amplifier at upper bass frequencies. The sealed system requires about 80 watts to reach 105 dB SPL.

The efficiency comparison at a low frequency of 40 Hz is also advantageous to the subwoofer employing the EQSS™ technique. The conventional subwoofer in a 28L sealed enclosure has a response that is down 4.3 dB at 40 Hz, resulting in a 40 Hz sensitivity of 85.7 – 4.3 = 81.4 dB SPL @ 1 Watt/1 Meter. In contrast, the EQSS™ subwoofer has an un-equalized QSS response that is down 8 dB at 40 Hz, resulting in a 40 Hz sensitivity of 91.5 – 8 = 83.5 dB SPL @ 1 Watt/1 Meter, fully 2.1 dB better than the conventional subwoofer.

The EQSS™-based subwoofer requires only 141 Watts of driving power from the power amplifier to produce its ELSPL of 105 dB SPL at 40 Hz. This is a very modest amount of required amplifier power for a subwoofer housed in an enclosure that provides only one cubic foot of available volume. This demonstrates yet another advantage of the EQSS™ technique, namely higher efficiency.

With an $f3$ of 46 Hz, the sealed subwoofer here could actually benefit from the use of a Linkwitz Transform. Let's see what happens when the Transform is used to give the sealed subwoofer the same $f3$ and Q as the small-box EQSS™ subwoofer. At the 30 Hz frequency where the EQSS™ subwoofer is still capable of 105 dB SPL, the sealed subwoofer is way down in performance, but it is still instructive to make the comparison.

The response of the sealed subwoofer is down 8.5 dB at 30 Hz and its ELSPL is down to 102 dB SPL. It is thus fully 3 dB less capable of SPL at the 30 Hz 3-dB frequency than the EQSS™ subwoofer, even though the latter employs a less expensive driver. Its efficiency at 30 Hz will be equal to its reference efficiency less the amount by which its frequency response is down at 30 Hz, or 85.7 dB – 8.5 dB = 77.2 dB.

By comparison, the EQSS™ subwoofer starts with a reference efficiency of 91.5 dB and its QSS response is down 12.2 dB at 30 Hz, resulting in a 30 Hz efficiency of 91.5 – 12.2 = 79.3 dB SPL. This is 2.1 dB better than the efficiency of the sealed system example.

The comparison is summarized as follows:

	Equalized Sealed	EQSS	
• Mid-bass efficiency	85.7	91.5	dB SPL
• Amplifier Power (MB)	85	22	Watts
• Efficiency at 30 Hz	77.2	79.3	dB SPL
• Amplifier Power (LF)	600	370	Watts
• SPL at 30 Hz	102	105	dB SPL
• Xmax	15	5.5	mm

Amplifier Power is the required power to achieve 105 dB SPL at Mid-bass frequencies (MB) or at 30 Hz (LF).

It is also instructive to compare the EQSS small-box sub to a non-equalized conventional sealed sub that is designed to have the same $f3$ and ELSPL as the EQSS design. Such a subwoofer can be realized in a one-cubic-foot enclosure using a driver with the following characteristics:

Vas	50 L
fs	18 Hz
Qts	0.42
Qes	0.47
Xmax	21 mm
D	21.5 cm
Efficiency	79.8 dB SPL
Vbox	28.2 L
$f3$	30 Hz
$f6$	23 Hz
Q	0.70
ELSPL	105 dB @ 30 Hz

This driver requires a very large Xmax in order to provide the same 105 dB SPL at 30 Hz as the EQSS driver whose Xmax is only 5.5 mm. The comparison is summarized as follows:

	Sealed	EQSS	
• Mid-bass efficiency	79.8	91.5	dB SPL
• Amplifier Power (MB)	330	22	Watts
• Efficiency at 30 Hz	76.8	79.3	dB SPL
• Amplifier Power (LF)	660	370	Watts
• SPL at 30 Hz	105	105	dB SPL
• Xmax	21	5.5	mm

Notably, the required excursion for the EQSS system is smaller by a factor of nearly four as compared to the sealed system. Note that in a conventional non-equalized system (like the sealed one above) efficiency at its 3 dB frequency will always be down 3 dB from its reference efficiency.

12. Comparison to Servo-controlled Subwoofers

Some high-quality subwoofers incorporate servo-controlled sealed systems. The servo control of the cone motion is implemented primarily to reduce the distortion that occurs in high-excursion subwoofers when high output is required. Most often, the servo control system is implemented with a special woofer driver that incorporates an accelerometer sensor into the moving part of the cone, sometimes located under the dust cap. Distortion is reduced by essentially including the moving cone in a feedback loop.

Because the purpose of the servo system is to reduce distortion due to large excursion in a sealed system, it is useful to compare this approach to the EQSS™ approach wherein less excursion is required in the first place. Assume, for the comparison, that a driver with the same Xmax and motor structure is used in both approaches, and in the same cabinet volume.

If the woofer is designed with good symmetry, most distortion will be of the third order. In this case, distortion percentage will tend to be proportional to the square of excursion. All else remaining largely equal, the EQSS™ implementation will require about ¼ the amount of excursion for a given ELSPL at 30 Hz as compared to the sealed version. This was illustrated in the comparison above. Distortion will then be on the order of 1/16 that of a non-servo sealed system. Since it is unlikely that the servo control can reduce distortion by a factor as great as 16, it would appear that the EQSS™ approach is superior and less expensive.

13. Comparison to Conventional Vented Subwoofers

In the example above we compared an EQSS™-based subwoofer in a small enclosure with a sealed alternative in the same size enclosure. The other alternative to an EQSS™ subwoofer is a vented subwoofer with a driver specially designed for a small enclosure. Such a design can incorporate either a large vent or a passive radiator.

As with a small-box sealed subwoofer, the driver for a small-box vented subwoofer usually must be designed with an unusually large cone mass. In other respects, such as achievable SPL for a given driver Xmax, the conventional vented system will perform similarly to the EQSS™ system for the same box tuning frequency. It will thus retain the advantage of requiring less Xmax for a given ELSPL as compared to a sealed system.

The "conventional" ported small-box subwoofer does not enjoy the advantage of EQSS™ wherein the roll-off below the pass-band is 12 dB/octave for nearly an octave below $f3$. It also does not benefit from the fact that frequency response and large-signal design (e.g., ELSPL) are divorced in an EQSS™ design. This places certain demands on the driver in order to achieve a flat frequency response. These demands include the need for large cone mass and low Qts.

A small-box vented subwoofer with the same box size and 3 dB frequency as the 10-inch EQSS™ subwoofer of *Figure 8* was designed using a synthesized driver assigned the following characteristics and providing the following performance:

Vas	85 L
fs	18 Hz
Qts	0.25
Qes	0.30
Xmax	5.5 mm
D	21.5 cm
Efficiency	84 dB SPL
Vbox	28.2 L
fb	30 Hz
f3	30 Hz
f6	27 Hz
ELSPL	104 dB @ 30 Hz

This vented subwoofer provides the same low-end performance as the EQSS™ subwoofer, but it requires a much more expensive driver and has much lower efficiency over most of the frequency band due to the required large cone mass. Its frequency response also falls off much more sharply below the 3-dB point than that of the EQSS™ subwoofer.

The comparison is summarized as follows:

	Vented	EQSS	
• Mid-bass efficiency	84.0	91.5	dB SPL
• Amplifier Power (MB)	126	22	Watts
• Efficiency at 30 Hz	81.0	79.3	dB SPL
• Amplifier Power (LF)	250	370	Watts
• SPL at 30 Hz	104	105	dB SPL
• Xmax	5.5	5.5	mm

Notably, the conventional vented subwoofer needs only the same Xmax as the driver used in the EQSS arrangement. This is to be expected, since they have the same cone area and are ported at the same frequency. The conventional vented subwoofer is much less efficient than the EQSS subwoofer at most frequencies, but in fairness it is about 1.7 dB more efficient at 30 Hz (partly as a result of the very large magnet that it must employ in order to achieve a Qts of 0.25 with such a heavy cone).

14. Thermal Considerations

As noted above, the efficiency of the EQSS™ system is a function of frequency. At very low frequencies, its efficiency is similar to that of a conventional ported subwoofer of the same performance. At upper-bass frequencies, however, the efficiency of the EQSS™ subwoofer increases significantly, while that of the conventional ported subwoofer remains the same.

This means that, on average, with program material whose low-frequency content is evenly distributed across the LF band, the power applied to the EQSS™ driver will be substantially less than that applied to the conventional ported subwoofer. This means that the EQSS™ subwoofer will dissipate less heat on average and tend to run cooler. The designer can thus choose a cooler-running voice coil producing less compression at high levels. Alternatively, the designer can use a less-expensive driver that can be designed with a lower average power capability. Of course, one may also choose a combination of these advantages together.

15. Driver Cost

It is notable that the woofer driver employed in the EQSS™ subwoofer illustration in *Figure 8* above is a conventional woofer not specifically designed for a subwoofer application (a 10-inch Dayton II woofer). With a value for Xmax of only 5.5 mm, this is not an expensive driver.

In contrast, drivers designed specifically for a sealed subwoofer application often have Xmax values in the range of 10 – 20 mm. Drivers designed to have large Xmax usually require much longer voice coils, causing less of the voice coil to reside in the magnetic gap at any given moment. Gap tolerances in such a long-excursion driver must often be larger to avoid scraping due to coil wobble. The larger tolerances tend to weaken the magnetic field in the gap. All of these factors conspire to require a much larger and more costly magnet assembly in order to realize a given set of driver T/S parameters.

Conventional sealed and ported small-box subwoofers must also employ drivers with higher cone mass. A driver with a higher cone mass, all else remaining equal, must employ a higher Bl product in order to achieve a given Qes. This further increases magnet assembly cost. The fact that EQSS™ relaxes the need for high cone mass thus allows the use of a less costly driver with a lighter cone.

16. Excursion Control

Vented boxes provide almost no restoring force to low-frequency cone excursion at frequencies below the box tuning frequency. This can result in potentially large cone excursions in the very low-frequency region for certain program material. This, combined with the low-frequency equalization gain provided by the EQSS™ equalizer, makes it often desirable to incorporate some form of high-pass filtering below the pass-band or excursion control into EQSS™ systems. If filtering is used, we would like to do it in such a way that we don't end up giving up too much of the transient response advantage that EQSS™ has over conventional vented systems.

In comparing EQSS™ systems with vented systems using the same driver Xmax and the same box tuning frequency, we find that they will both have the same amount of excursion as a function of program material and program amplitude down to the system 3 dB frequency. This will be the case in spite of any EQSS™ equalizer gain down to that frequency. However, below that frequency, any further EQSS™ equalizer gain will cause increased excursion in comparison to the conventional vented system. Using *Figure 7* as a typical example, we can see that the EQSS™ equalizer adds about 1.0 dB of additional equalization below the system 3 dB point down to d.c. This suggests that an EQSS™ system is typically only 1 dB or so more prone to over-excursion at frequencies below the pass-band than an equivalent conventional vented system.

Figure 12 shows a block diagram illustrating one of many approaches to excursion control. In this approach a subsonic filter is employed that normally has a low cutoff frequency, perhaps on the order of 10 Hz. However, its cut-off frequency can be electronically controlled so as to increase to a higher frequency if the driver is in danger of over-excursion. The driver's excursion is modeled by a filter circuit that operates on the signal fed to the power amplifier. If the estimated excursion approaches the limit, the control circuit causes the corner frequency of the subsonic high-pass filter to increase. It will be increased by the amount necessary to attenuate the low frequencies enough to avoid over-excursion. The benefit of this approach is that under normal smaller-signal conditions, when excursion control is not needed, the filter has very little effect on the transient characteristics of the signal.

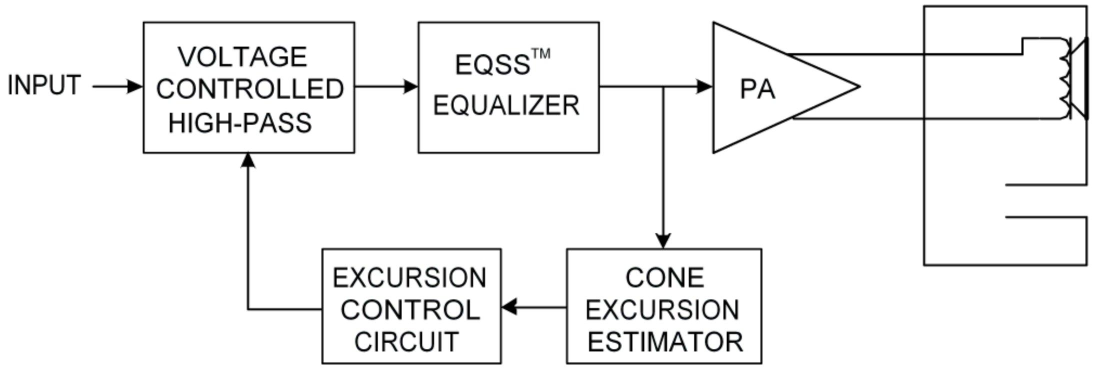


Figure 12: Typical Excursion Control System

17. Conclusion

The EQSS™ technology offers numerous advantages over conventional sealed and vented low-frequency systems in active applications where equalization at line level can be applied. These applications include subwoofers and active loudspeaker systems. Advantages include the ability to employ small drivers where good bass extension is required, and the ability to implement efficient subwoofers in small boxes.

The advantages of the EQSS technology can be summarized as follows:

- Superior ELSPL compared to sealed systems
- Smaller required Xmax compared to sealed systems
- Superior transient response compared to vented systems
- Superior average efficiency
- Reduced driver cost
    - less required Xmax
    - smaller magnets
    - reduced average power dissipation
- Frequency response divorced from large-signal considerations

The EQSS™ technique is a patent-pending technology that is available for licensing. Custom design services for EQSS-based loudspeakers and systems are also available.