The Effect of the MaxxBass\textsuperscript{1} Psychoacoustic Bass Enhancement System on Loudspeaker Design

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Abstract

The MaxxBass signal processing algorithm is introduced as a new factor in low frequency loudspeaker design. Exploiting the phenomenon of the ‘missing fundamental’, MaxxBass stimulates a low frequency auditory sensation without the need to produce the whole low frequency range. A brief review is made of the performance limitations in the bass reproduction of small speakers with emphasis upon the difficulty of efficiently lowering the resonant frequency. The breakdown in the ear’s logarithmic sensitivity at low frequencies is identified as a factor for satisfactory bass performance. With MaxxBass correctly implemented, gains in apparent low frequency extension of up to one and a half octaves are reported. Example applications of MaxxBass are explored.

Introduction

In every loudspeaker at every price range, the designer looks to provide a more extended, linear and dynamic bass response. This is a significant challenge. The faithful reproduction of low frequency audio is the most difficult and costly goal in loudspeaker design. Any constraint on size and budget quickly impairs a loudspeaker’s bass performance. This perhaps explains why the average consumer regards the low frequency extension of a medium-fidelity system as its most tangible measure of performance, heavily influencing the system’s desirability. With an increasing amount of low frequency content in popular music and film soundtracks, the modern consumer demands an experience that recreates the pop concert, the disco and the cinema at home. It falls to the loudspeaker designer to maximise the low frequency performance of the audio system with due consideration to the physical and commercial constraints. These constraints vary greatly from situation to situation, but most commonly include

- a fixed production cost,
- a minimal size,
- a maximal efficiency.

A theoretical framework has been developed to help the designer achieve maximum low frequency performance and this is often embodied in computer aided design software. In the main, such design procedures work well; however, when the boundaries are stretched, for example involving miniature enclosures or very high sound levels, those general theoretical guidelines define the solution less accurately. Furthermore, neither the theory nor the CAD software considers important factors of human perception. Properly taken into account, they allow the designer a new degree of freedom within which to optimise performance to the technical limitations. If these factors remain unexploited the design is likely to be sub-optimal, and in today’s difficult market, uncompetitive. A well-known example is the ear’s higher tolerance of harmonic distortion at low frequencies. Without this crucial knowledge, a designer may try to produce a loudspeaker with a maximum 2% distortion throughout its range. Although admirable in theory, the false sense of importance attached to this aim would certainly introduce compromises elsewhere in the design for no audible gain.

\textsuperscript{1}MaxxBass is a patented technology of Waves Ltd.
MaxxBass represents a new design factor in low frequency loudspeaker design. Essentially, it is a patented audio signal processing algorithm expressed in analogue or digital form. Correctly implemented it can extend the apparent low range of the loudspeaker by up to one and a half octaves with no loss of efficiency, no increase in power input and no increase in size. This could only otherwise be attained at substantial cost. To understand how this is achieved it is best to briefly outline some theory.

MaxxBass exploits the psychoacoustic phenomenon of the ‘missing fundamental’. This phenomenon involves the pitch perception of complex tones. Investigating the auditory perception of combination tones, Schouten [1] showed that complex periodic sounds with no energy at the fundamental may still give a clear pitch sensation at the fundamental. This would indicate that low pitches may be perceived via those neural channels that normally respond to the high or middle frequency components of a signal. Several models have been proposed, these falling into two broad classes: the ‘pattern recognition’ models and the ‘temporal’ models. Although examining these models falls outside the scope of this paper, a simple visual example of a ‘pattern recognition’ phenomenon is presented in Figures 1 and 2. Figure 1 is strongly suggestive of a triangle; figure 2 of a cube. In fact, it is quite difficult for the mind to disassociate the three parts of figure 1, and similarly it is difficult for the mind to see figure 2 as a square adjoined by two rhombi. Both figures are seen as a whole or a ‘gestalt’, the mind recognising a pattern and then fulfilling its own expectations of this pattern. The precise mechanism of the ‘missing fundamental’ is still under investigation; there is strong evidence for the theory that the brain determines the pitch of a complex sound according to its periodicity.

In a section titled ‘The Case of the Missing Fundamental,’ Beranek [2, Sc. 13.6] notes the puzzlement caused by the ability of some small loudspeakers to sound ‘reasonably well’ in a low frequency range in which they can generate no significant power. The reason for their surprising performance, he suggests, is that the bass notes are supplied physiologically or psychologically because several of their harmonics are present in the signal. ‘The perceived pitch of a combination of tones spaced equally in frequency is usually not that of the mean frequency, but rather that of the constant difference frequency.’ He goes on to note that this effect is especially powerful if just the ‘right amount’ of harmonics is produced. The MaxxBass algorithm takes the vagaries out of this effect, controlling and maximising it in line with current psychoacoustic theory.

To create auditory sensation below the loudspeaker cutoff frequency, \( f_3 \), MaxxBass divides the audio signal into two frequency passbands around \( f_3 \). For each frequency present in the lower band (a fundamental), MaxxBass generates a carefully weighted series of upper band harmonics designed to stimulate an auditory sensation at the loudness and pitch of the original fundamental. MaxxBass filters out the lower passband using a 24 dB/octave high pass filter, and then combines the generated harmonics and the original higher passband signal into one that contains information relevant to both the low and high frequency bands. In this way, MaxxBass allows the loudspeaker to operate at its reference efficiency while retaining psychoacoustically weighted information from all parts of the original frequency spectrum.

Figure 3 is a schematic diagram of the operation of MaxxBass on a signal composed of two frequencies (50Hz, 140Hz) and optimised for a loudspeaker cutoff of 90Hz. MaxxBass creates a harmonic image for each fundamental frequency below its cutoff frequency matched for pitch and loudness. For fundamentals down to the half the cutoff frequency, \( (i.e. \text{one octave below cutoff,}) \) the harmonic image consists primarily of the 2\(^{nd}\) and 3\(^{rd}\) harmonics. For fundamentals down to a third of the cutoff, \( (\text{approximately one and a half octaves,}) \) the harmonic image consists primarily of the 3\(^{rd}\) and 4\(^{th}\) harmonics. Frequencies below this will not be efficiently rendered. The harmonic’s dynamic range is controlled such that their perceived loudness (in phons) will match that of the (intended) original fundamental according to the equal-loudness contours (described below). This allows MaxxBass to stimulate auditory sensation up to one octave below its cutoff frequency. Figure 4 shows the power spectral density of a 50Hz sine wave before and after processing.
There are two major factors responsible for the difficulty in designing small full-range speakers that fulfil the criteria outlined above. These will be dealt with below.

**Low frequency auditory sensation**

One factor responsible for poor apparent bass response from loudspeakers is the ear’s non-linear hearing response. Figure 7 is a graph showing a set of equal loudness level curves derived from the data of Fletcher-Munson [9]. These curves relate the subjective loudness level of a pure tone, measured in phons, to the tone’s frequency and intensity. The phon is calibrated with a pure tone at the reference frequency of 1000Hz and is defined to be numerically equal to the intensity level of this tone measured in decibels; this can be quickly verified with Fig. 7. To measure the loudness level of tones at other frequencies, the volume of the 1,000-hertz reference tone is adjusted until it is perceived by listeners to be equally as loud as the sound being measured. The measured intensity of the reference tone now denotes the loudness level of original sound.

We immediately note that the ear’s sensitivity to bass frequency falls as we descend the frequency scale. A small loudspeaker that has traded sensitivity for a bass response down to 40Hz may produce a maximum sound intensity of 60dB. Using the graph we see that at 1,000 Hz this relates to a loudness level of 60 phons, whereas at 40 Hz this is close to the threshold of hearing and therefore close to useless.

The ear’s frequency dependent sensitivity is an inherent characteristic of all auditory experience; a sudden ‘levelling’ of these curves would sound unnatural. Of greater importance is the slow breakdown of the logarithmic sensitivity to one that is increasingly linear. This can be seen by noting that in the bass frequencies (20-100Hz) the graph becomes increasingly steep as we decrease the intensity level. In this frequency range, not only is the ear less sensitive to sound but small changes in sound level are critical. The attenuation of the bass frequencies may quickly render them inaudible.

We can formalise the relationship given in Fig. 7 by defining the *equal loudness level function* so

\[ ELL(I, f) \text{ [phons]} \]

where,

- \( I \) intensity level of tone \([\text{dB}]\)
- \( f \) frequency of tone \([\text{Hz}]\)

**The effect of MaxxBass on loudspeaker performance**

Using this relationship we define a loudspeaker’s *phon response* to be the loudness level of the auditory sensation produced by driving it with a fixed power audio signal throughout the useful frequency range (20Hz-20kHz). We can now state more precisely the effect of MaxxBass on loudspeaker performance. MaxxBass extends the phon response of a loudspeaker by up to one and a half octaves. Furthermore, as MaxxBass generated harmonics are in a higher frequency range than the fundamental they are simulating, the audio signal is far less susceptible to the fall in the ear’s sensitivity at low frequencies.

By working wholly in the reference frequency range, MaxxBass guarantees maximal system efficiency with minimum compromise. Including MaxxBass in the design process allows for powerful changes in specification and performance. Thus, the designer is able to reconfigure to create a completely new alignment. For the driver, the higher \( f_c \) allows for a lighter more efficient cone, while the new alignment allows for a substantially more compact enclosure. In addition, the raised sensitivity potentially allows for higher maximum sound level before the onset of audible distortion.

**Low frequency loudspeaker performance**

A loudspeaker's low frequency performance is closely related to its closed-box resonant frequency, \( f_c \). Above \( f_c \), the loudspeaker is mass-controlled. Increasing frequency causes a decrease in cone excursion, but this is compensated by an increase in acoustic radiation resistance resulting in fairly uniform output. Below \( f_c \), the loudspeaker is compliance-controlled, the predominant impedance being that of the elastic restoring force, and bass output is attenuated by between 12 and 24 dB per octave [8]. The cost of compensating for a given high resonant frequency with low frequency amplification is prohibitive. While the obvious solution is to lower the resonant frequency of the loudspeaker this can prove just as difficult. As an instructive example, simple closed-box loudspeaker design equations relating cutoff frequency, \( f_3 \), to other important quantities are given below after Small [6]. All symbols used in the following are defined in the glossary.
The reference efficiency, $\eta_0$, of the loudspeaker is the efficiency of the speaker for the portion of the piston band above $f_3$, and is related to $f_3$ by

$$\eta_0 = k_\eta V_b (f_3)^3$$

where $k_\eta$ is an efficiency constant as defined by Small [6, eq. 27]. A halving of the system cutoff frequency would result in an eight-fold decrease in efficiency.

At moderately high frequencies, diaphragm excursion is small and the driver’s power handling is limited by its ability to dissipate heat. At lower frequencies, a greater excursion is required and the input is often limited by driver’s the maximum linear excursion (i.e. displacement). The displacement limited power output, $P_{AR(CB)}$, is given by

$$P_{AR(CB)} = K_p f_3^4 V_D^2$$

where $K_p$ is a power rating constant [6, eq. 41], (which varies with $Q_{TC}$) and the volume displacement, $V_D$, is the product of $S_D$ and the maximum linear excursion, $X_{max}$. Greater power input will cause significant distortion.

We immediately see that halving the cutoff frequency decreases $P_{AR(CB)}$ sixteen-fold. This can be compensated with a four-fold increase in cone radius or a sixteen-fold increase in maximum linear excursion. Figure 5 illustrates the dependence of maximum attainable efficiency upon box volume (in litres) and cutoff frequency. With the graph we can immediately see that with parameters $\eta_0=2\%$, $V_b=20$ litres and $f_3=80$ Hz, to half the cutoff frequency while keeping the efficiency constant would require a box volume increase to about 160 litres. Alternatively keeping volume constant would cut efficiency to 0.3%.

Figure 6 illustrates the dependence of maximum attainable displacement limited power output and volume displacement ($V_D = S_D X_{max}$) on cutoff frequency. Here we can see the significant increase in linear cone displacement and effective cone area needed to counterbalance a halving of cutoff frequency. There is, of course, no quick fix to halving the cutoff frequency of a loudspeaker system. A balanced system requires careful design, the equations above relating to maximal efficiency and power output of ideal systems.

Although these results above are concerned with sealed-box system analysis, results similar to these obtained with vented box analysis. Designers are faced on a daily basis with these very real barriers.

In difficult situations, designers might be tempted to raise the total system $Q_{TC}$, but find there they quickly run into a loss of quality. Increasing the value of $Q_{TC}$ from the Butterworth maximally-flat response ($Q_{TC} = 0.707$) results in an underdamping of the voice-coil at the loudspeaker’s resonant frequency, $f_C$. This causes a peak in the response around $f_C$ and a relative increase in bass extension. Further increasing $Q_{TC}$ increases the response peak, but not the system bandwidth. Systems with alignments such as this will produce palpably more bass, but no more bass extension. Furthermore, such systems will suffer poor transient response associated with underdamped systems producing a smearing and boominess. Taken to extremes, this procedure results in the ‘one-note’ system.

The effect of bass boost circuitry is to amplify the audio signal two to four octaves around $f_C$. Above $f_C$, the loudspeaker operates at its reference efficiency and amplification of the audio signal in this range amplifies the acoustic output more or less linearly. At low volume, this can ‘warm’ the tone of the loudspeakers increasing the perceived bass response. Below $f_C$, the efficiency of the loudspeaker falls at between 12 and 24 dB per octave. To extend the linear bass response by an octave would require low frequency amplification of the order of between 18 and 42 dB - a very expensive solution. A more modest amplification of 5-6db can extend the frequency range by one third of an octave. However, the loudspeaker’s dynamic range is reduced and it can quickly reach the limit of its linear diaphragm excursion resulting in unpleasant and uncontrolled distortion.

**Practical applications of MaxxBass**

MaxxBass can demonstrably give psychoacoustic bass enhancement of up to one and a half octaves. In the example below, however, we conservatively assume that an extension of one octave is attained. In this case, all of the harmonics generated by MaxxBass are contained in the upper passband and are therefore reproduced by the speaker. This allows MaxxBass to operate with maximal effect.

Figures 8 and 9 show example alignments for two systems, Figure 9 being designed for use with MaxxBass. The table below summarised their major specifications.
Comparing the two examples with and without MaxxBass, we have a common size of driver, a 130 mm (5 in) driver, initially in a 11.7 litre closed box. The driver in speaker A has a low resonant frequency caused by its heavy cone. This gives it a low efficiency of 0.85% but ensures a reasonable cutoff of 77 Hz. The bass enhancement allows the designer to use a lighter cone giving the driver an 5-fold efficiency increase in this case. Furthermore, the box volume has decreased by over 42%. The reduction of enclosure size is, of course, highly desirable in itself. The maximum SPL, being the minimum value of thermal and displacement limited SPL, is increased by 6dB in the case of the bass enhanced speaker. It is perhaps this performance increase that would most appeal to the consumer.

The cutoff frequency of the second system is somewhat under twice that of the traditional system. This is where psychoacoustic bass enhancement makes an impact. Although the precise calculation of loudspeaker phon response currently requires large scale experiment, to a first approximation we can say that without dynamic range control (DRC) the algorithm extends the perceived bass response by an octave; with DRC a maximum bass extension of one and a half octaves is possible.

We can see that there is a major change in the performance and value of the second system over the first, showing the power of psychoacoustic processing in generating new alignments and improved performance. The designer can, of course, choose simply to extend the bass response or maximally decrease the box volume of his current loudspeaker. Thus the algorithm does not prescribe a course of action or new alignment, but allows for a new degree of freedom in speaker design.

The applications of MaxxBass are, of course, not limited to sealed box speakers. Traditional consumer markets like radio, television, ‘ghetto blasters’ could all benefit from the careful application of this new tool. Consumer electronics companies have even greater challenges in the near future. With multimedia computing becoming standard, mobile computing getting more affordable and the first generation of flat panel televisions being manufactured, the need for better bass performance with very limited resources will become a routine task for the busy speaker designer. The availability of microprocessors, once perhaps a disincentive to the inclusion of signal processing, is almost universal in these consumer products; the application of signal processing should, and perhaps will, become an integral part of knowledge and experience that loudspeaker designers bring to their projects.

**Conclusions**

This paper seeks to inform loudspeaker designers of a new technique in perceptual coding that can help to achieve impressive performance under a tight budget. With psychoacoustic bass enhancement as part of the design process, system designers will be able to maximise the balance of performance and efficiency. The examples are illustrative of, but by no means constrain the possible implementations of the MaxxBass algorithm. Using this tool, inventive designers will be able to push the envelope of commercial loudspeaker design.

**Further Work**

This paper represents preliminary work exploring and quantifying the effect of the MaxxBass algorithm in loudspeaker design. Further avenues of investigation include new alignments for bass reflex, multiple driver and ‘subwoofer’ types of loudspeaker. Of greater scope would be research into an accurate way of measuring a speakers phon response, which holds the promise of an objective way of assessing a speakers loudness level throughout the frequency range.
Glossary

Below are the symbols used in the analysis above:

\( f_C \) closed box resonance
\( f_S \) free air resonance of driver
\( f_3 \) cutoff (-3dB) frequency of the system
\( K_P \) power rating constant
\( P_{E\text{\text{\text{\text{\text{\vspace{-1em}max}}}}} \) thermally-limited maximum input power
\( Q_{ES} \) Q of driver at \( f_S \) considering \( R_E \) only
\( Q_{MS} \) Q of driver at \( f_S \) considering non-electrical resistances only
\( Q_{TS} \) total Q of driver at \( f_S \)
\( Q_{TC} \) total system Q
\( S_D \) effective diaphragm area
\( SPL \) sound pressure level (see Beranek [1, p.14] for definition)
\( V_{AS} \) volume of air with same acoustic compliance as driver suspension
\( V_B \) internal box volume
\( V_D \) volume displacement
\( X_{\text{max}} \) maximum linear excursion
\( \eta_0 \) reference efficiency of loudspeaker system
\( \alpha \) system compliance ratio \( (V_{AS} / V_B) \)

References

Figures 1 and 2: Simple visual examples of pattern recognition

Figure 3: Schematic diagram of the operation of the MaxxBass algorithm
Figure 4: Comparison of PSDs for 50Hz sine wave and its MaxxBass processed counterpart.

Figure 5: Relationship between cutoff frequency and loudspeaker box volume [6]

Figure 6: Relationship between cutoff frequency and displacement – limited power output [6]
Figure 7: Equal loudness-level curves derived from Fletcher-Munson data [9]

Figure 8: SPL response for traditional sealed-box speaker alignment
Figure 9: SPL Response for sealed-box speaker aligned for use with MaxxBass signal processing