# Optimally sensitive and efficient compact loudspeakers for low audio frequencies

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**Abstract**
Conventionally, the ultimate goal in loudspeaker design has been to obtain a flat frequency response over a specified frequency range. This can be achieved by carefully selecting the main loudspeaker parameters such as the enclosure volume, the cone diameter, the moving mass and the very crucial "force factor". For loudspeakers in small cabinets the results of this design procedure appear to be quite inefficient, especially at low frequencies. This paper describes a new solution to this problem. It consists of the combination of a highly non-linear preprocessing of the audio signal and the use of a so called low-force-factor loudspeaker. This combination yields a strongly increased efficiency, at least over a limited frequency range, at the cost of a somewhat altered sound quality. An analytically tractable optimality criterion has been defined and has been verified by the design of an experimental loudspeaker. This has a much higher efficiency and a higher sensitivity than current low-frequency loudspeakers, while its cabinet can be much smaller.

## Introduction

A cross-section of a very common electrodynamic loudspeaker is shown in Figure 1. Basically, the loudspeaker consists of a permanent magnet and a loudspeaker cone, to which the voice coil is connected rigidly. The voice coil is situated in an air gap in the permanent magnet, in which a magnetic flux density $B$ is present. If an electrical current $I$ flows through the voice coil, with effective length of wire $l$, a Lorentz force $F$ acts on the voice coil and hence on the loudspeaker cone, given by:

$$F = Bl\ I$$

The product $Bl$ is called the "force factor" and plays a very important role in the design process of loudspeakers. Additional components of the loudspeaker in Figure 1 are the frame, the cone suspensions and the dust cap.

In the audio world, much effort has been spent in obtaining a high sound output from compact loudspeaker arrangements. Here, the term "compact" refers to both the volume of the cabinet in which the loudspeaker is mounted and the cone area of the loudspeaker.

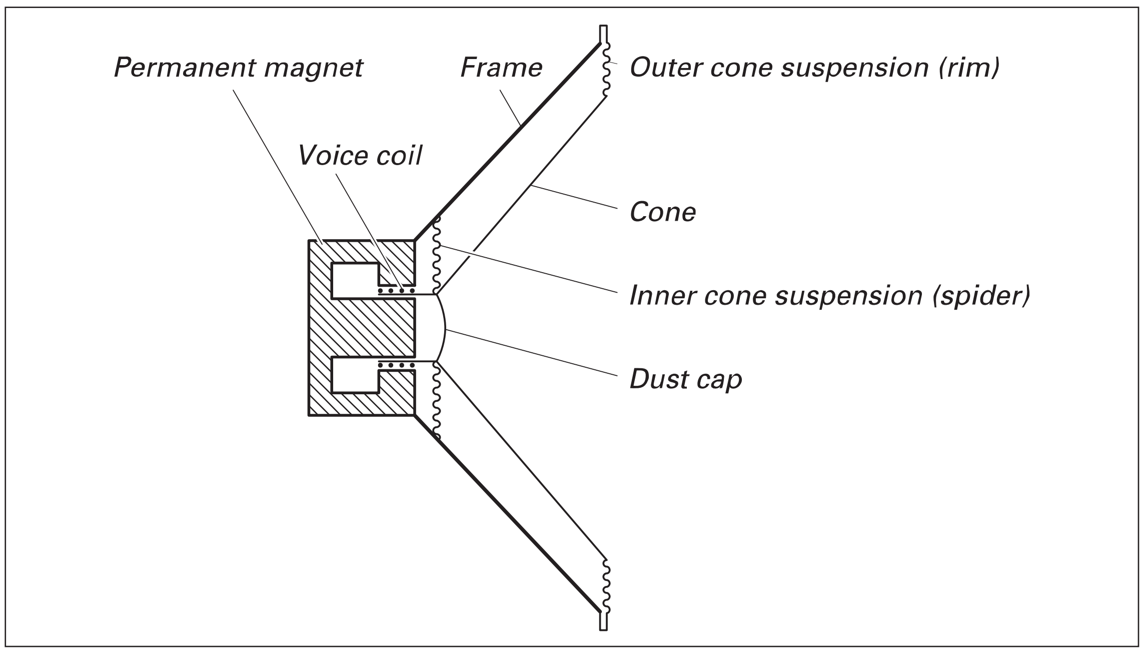


*Figure 1. Cross section of an electrodynamic cone loudspeaker.*

In principle, loudspeakers can be built in such a way that they properly reproduce the entire audible frequency spectrum, down to 20 Hz, but such systems are both expensive and very bulky. Therefore, in many of today's sound reproduction applications it is not possible to use them. Typical examples are portable audio sets, multi-channel sound systems and flat TV sets.

Various signal-processing schemes have been proposed to equalize the response of small loudspeakers or to use psychoacoustic enhancement methods; see Ref. 1. for an overview.

In this paper we will discuss a new and totally different approach to obtain almost optimal sensitivity and effiency in compact loudspeakers at low audio frequencies. This approach consists of two steps. First, we will use a special loudspeaker that is optimized at one particular frequency, namely its resonance frequency. Secondly, we will use non-linear signal preprocessing to compress the bandwidth of a 20-to-120-Hz audio bass signal down to a much narrower frequency span. This span is centered at the resonance frequency of the loudspeaker, where its efficiency is maximal. These loudspeakers are especially suited for use in so called subwoofers.

## Sensitivity and efficiency

Obviously, for any loudspeaker the perceived audio quality is very important, but also its sensitivity and efficiency are of great importance.

The sensitivity of a loudspeaker has been defined as the ratio of the sound pressure *P* at a certain distance from the loudspeaker and the voltage *V* applied. The sensitivity is frequency-dependent.

The efficiency of a loudspeaker has been defined as the ratio between the time-averaged acoustically radiated power $P_a$ and the time-averaged electrical power $P_e$ delivered to the loudspeaker. The efficiency, thus defined, is also a function of frequency.

It appears that, in general, electrodynamic loudspeakers with a very high efficiency have a poor sensitivity at low frequencies. Therefore, with conventional designs, it is not possible to combine a very high efficiency and a high sensitivity over a wide frequency range with a compact arrangement.

Mathematical formulas that express the exact relations between sensitivity and efficiency on the one hand and the main loudspeaker design parameters on the other hand have been derived (see: Refs. 2 and 3). They show the great importance of the force factor *Bl* on the two main loudspeaker performance criteria we are considering: sensitivity and efficiency.

Recently, Vanderkooy *et al.* (Ref. 4) investigated the performance of high-*Bl* loudspeakers. The aim of that study was to get efficient loudspeakers. However, they showed a poor sensitivity at low frequencies.

In the rest of this paper the performance and use of low-*Bl* loudspeakers will be discussed. It will be shown that these loudspeakers are highly sensitive and exhibit a good efficiency, but only around their resonance frequency.

## Graphical results

The main results of the theoretical analyses referred to in the previous section can be represented graphically. Figure 2 shows the typical sound pressure level SPL (in dB) of a particular loudspeaker at a distance of 1 meter as a function of frequency, for three different values of the force factor *Bl*, while all other parameters are kept constant. (SPL is directly related to the sensitivity of the loudspeaker.) The solid curve represents *Bl*=1.2 ("low *Bl*"), the dash-dot curve *Bl*=5 ("medium Bl") and the dashed curve *Bl*=22 ("high *Bl*").

It is seen in Figure 2 that the curves change drastically for varying *Bl*. The most prominent difference is the shape, but the difference in sound pressure level at high frequencies is also apparent. While the low-*Bl* device has the highest response at the resonance frequency, it has a poor response beyond resonance. The high-*Bl* device has a good response at higher frequencies, but a poor response at lower frequencies, which requires special equalization. In between, there is the well-known curve for a medium-*Bl* driver.

The influence of the value of Bl on the sensitivity specifically at the resonance frequency can be further clarified by plotting the SPL at the resonance frequency versus the normalized value of *Bl*, as shown in Figure 3. It appears that at the resonance frequency there is an optimal value for the voltage sensitivity at $Bl/Bl_o=1$, where $Bl_o$ is the optimum *Bl* value that can be derived from the theoretical analysis mentioned before.

Theoretical analysis also yields an expression for the efficiency *h* as a function of frequency. This is shown in Figure 4 for one particular loudspeaker for various values of the force factor *Bl*, while all other parameters are kept constant. The lower solid curve corresponds to *Bl*=1.2 ("low *Bl*"), the dash-dot curve to *Bl*=5 ("medium *Bl*"), the dashed curve to *Bl*=22 ("high *Bl*")and the upper solid curve to very large values of *Bl* ("infinite *Bl*").

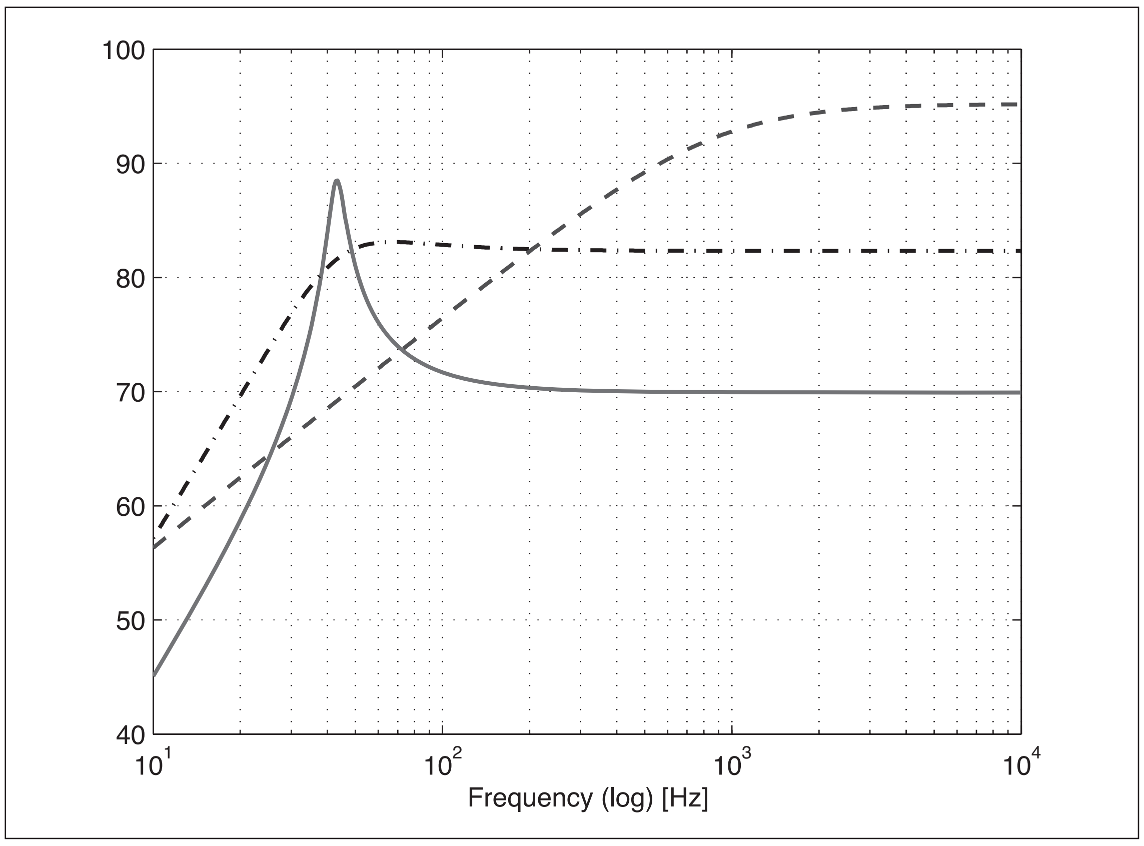


*Figure 2. Sound pressure level (SPL) as a function of frequency for three values of the force factor Bl: low Bl=1.2 (solid), medium Bl=5 (dash-dot) and high Bl=22 (dash), while all other parameters are kept constant (among which: input power = 1 W and distance = 1 m). At the resonance frequency, the highest SPL is obtained for low-Bl, while the high-Bl device has a poor response at low frequencies, in particular at the resonance frequency.*

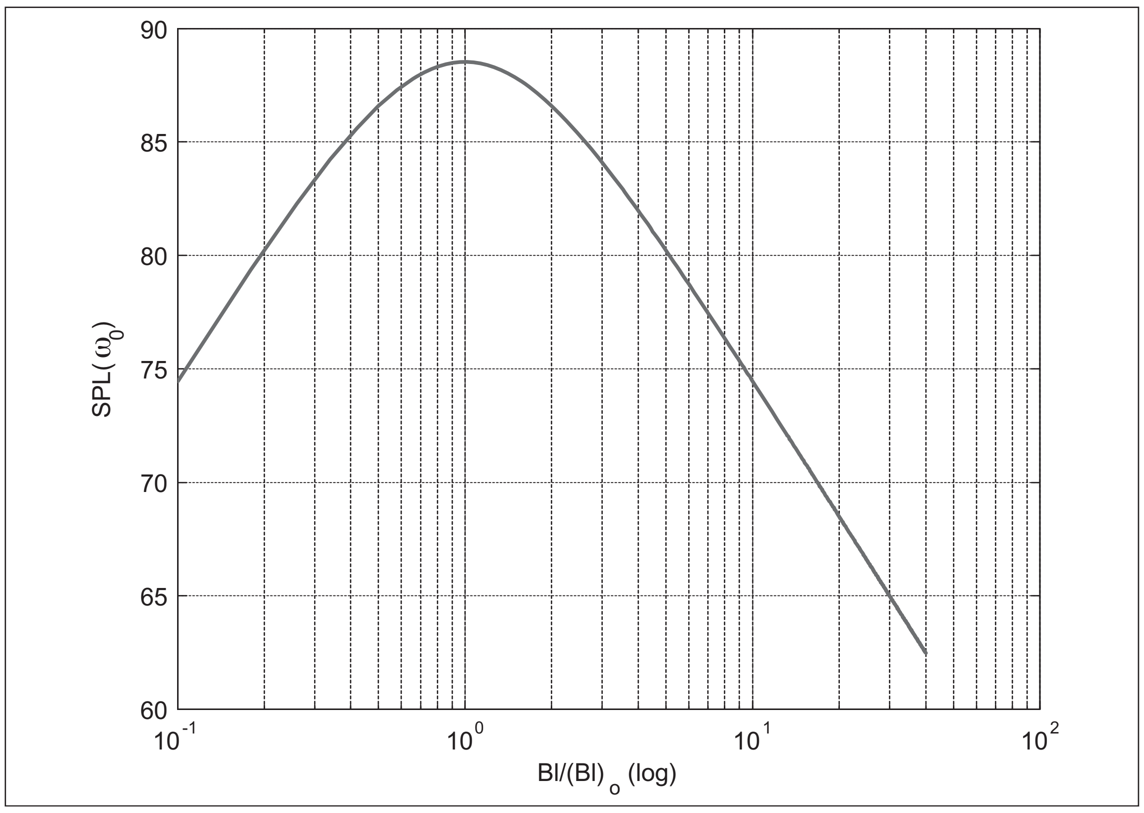


*Figure 3. The SPL at the resonance frequency versus the normalized force factor $Bl/Bl_o$, where $Bl_o$ is the optimum force factor value, which in the present case equals 1.19.*

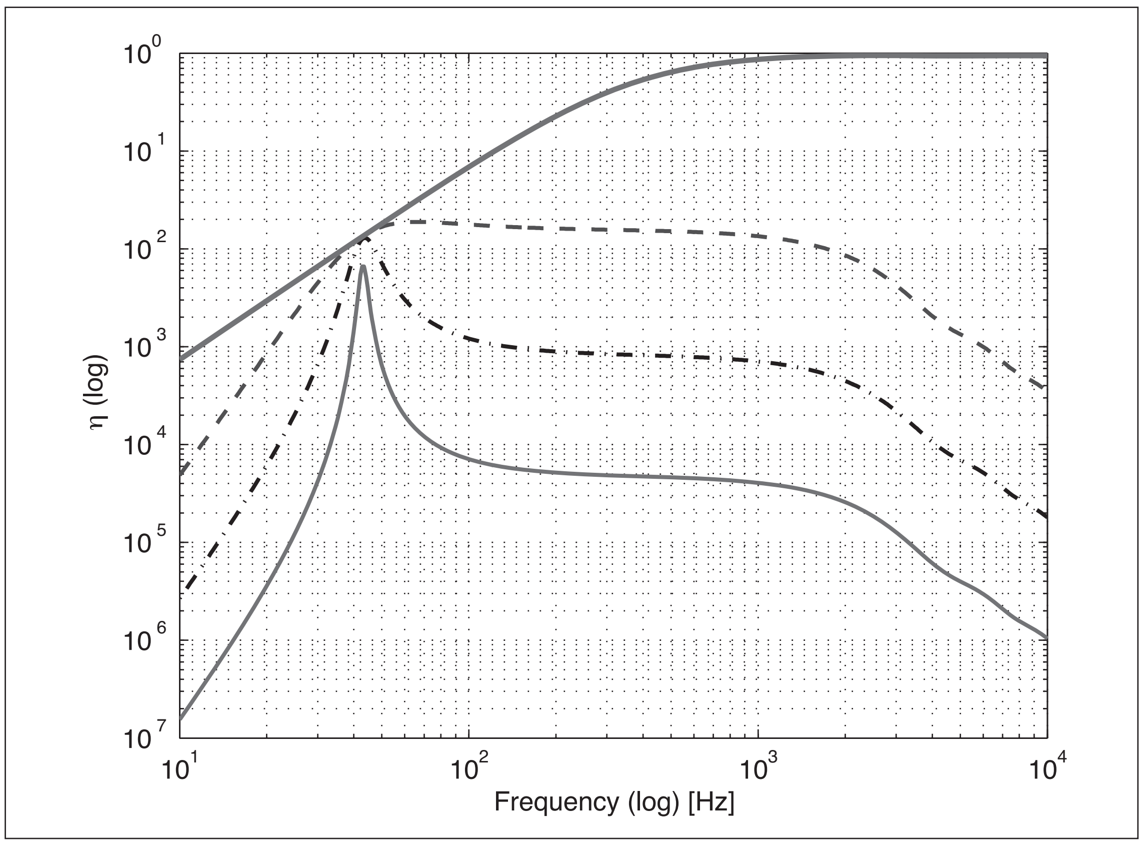


*Figure 4. The efficiency η for 4 values of Bl: low Bl=1.2 (solid), medium Bl=5 (dash-dot), high Bl=22 (dash) and very large Bl (thick solid), while all other parameters are kept constant. Note that the efficiency is strongly dependent on Bl at all frequencies except at resonance, where the efficiency varies only modestly with Bl.*

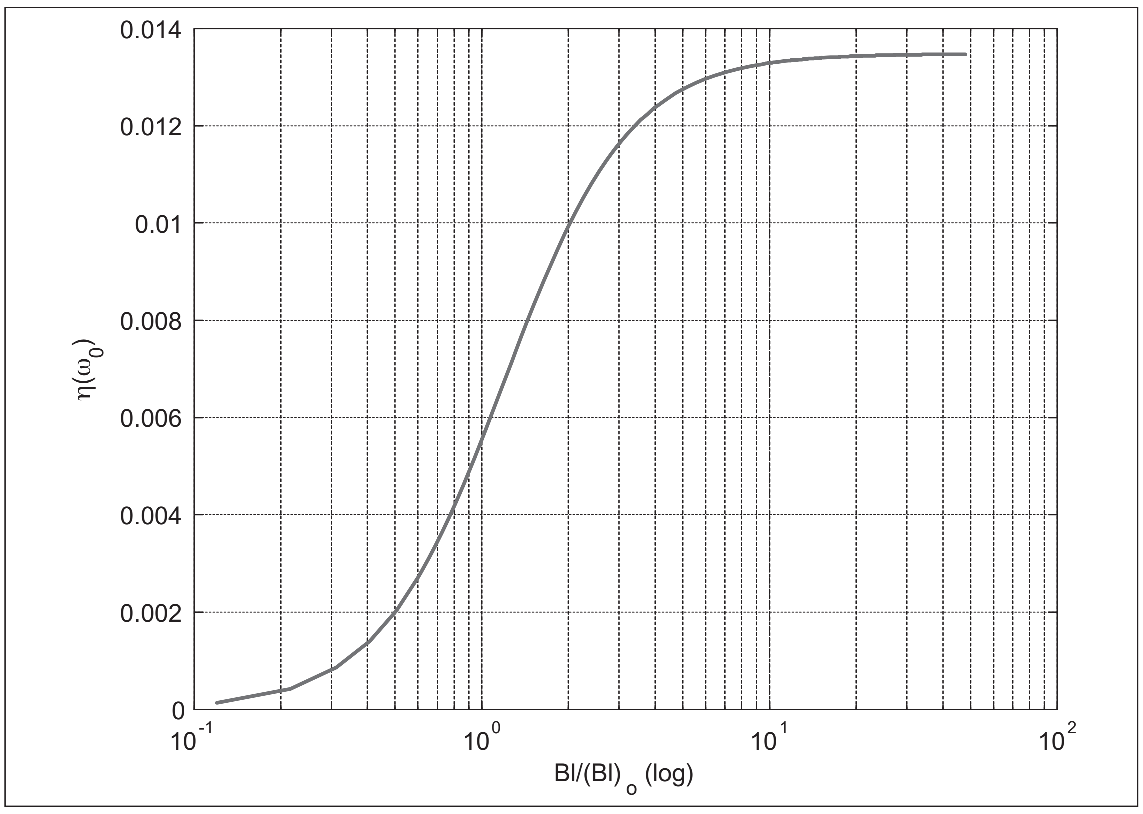


*Figure 5. The efficiency η at resonance versus the normalized force factor $Bl/Bl_o$, where $Bl_o$ is the optimum force factor value, which in the present case equals 1.19.*

It appears that the shape of these curves also changes drastically for varying *Bl*, but their values around the resonance frequency vary only modestly. This is further elucidated in the graph of Figure 5. This graph shows the efficiency at the resonance frequency versus the normalized value $Bl/Bl_o$, which we have used before in Figure 3. Figure 5 shows an s-curve, where the part for very low *Bl* values exhibits a very poor efficiency. There, the Lorentz force acting on the voice coil is small with respect to the damping. Then, for increasing values of *Bl*, a rather steep part of the curve follows and, finally, a plateau exists.

## Low-Bl loudspeakers

As mentioned before, low-frequency sound reproduction with the usual small transducers is quite inefficient. Now, in order to improve efficiency, we relax the requirement that the frequency response must be flat. This allows the magnet to be made considerably smaller and lighter. As a result, a large peak in the SPL curve (Figure 2 — solid curve) will appear. At the resonance frequency, the sensitivity can be a factor of ten higher than that of a normal loudspeaker. Moreover, the loudspeaker can now be of the moving-magnet type with a stationary coil, instead of the usual stationary-magnet type with a moving coil as shown in Figure 1. This has additional constructive advantages, such as the absence of moving litze wires, yielding increased life span.

Figure 6 shows the experimental MM3 loudspeaker that we have designed according to these guidelines. With this loudspeaker, we achieved an SPL of almost 90 dB at the resonance frequency at 1-W input power and 1-m distance, even when using a small cabinet (with a volume of less than 1 liter). However, due to the high and narrow peak in the frequency response, the normal operating range of the loudspeaker has decreased considerably. This makes it unsuitable for normal use, even as a subwoofer. To overcome this problem, we have added some non-linear signal pre-processing.

## Signal pre-processing

Nonlinear pre-processing of the input signal to the low-*Bl* loudspeaker can make it perfectly suitable for use in small subwoofers in the frequency range of, say 20 to 120 Hz. To this end, we use the non-linear processing scheme shown in Figure 7. This scheme compresses the bandwidth of the 2.5-octave-wide bass signal down to a much narrower span, centered at the resonance of the low-*Bl* loudspeaker, where its efficiency is maximum.

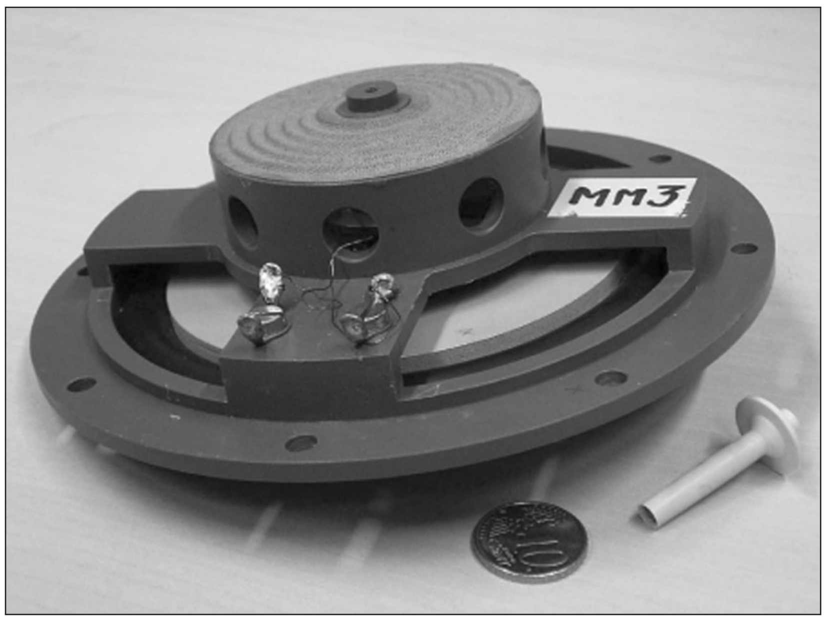


*Figure 6 Picture of the prototype low-Bl loudspeaker MM3 with a 10-eurocents coin in the lower middle for comparison purposes. At the position where a normal loudspeaker contains a heavy and expensive magnet, our prototype has an almost empty cavity, because only a small moving magnet is necessary. A copy of this magnet is shown in the lower right-hand corner.*

The preprocessing comprises a bandpass filter BPF, an envelope detector EnvDet and a modulator. EnvDet can be a simple rectifier followed by a lowpass filter. The output of EnvDet is used in a multiplier to modulate a sinusoid of fixed amplitude and frequency _, which is the resonance frequency of the low-*Bl* loudspeaker.

The result of this preprocessing is that the coarse structure (the envelope) of the music signal is preserved, but that the fine structure has been changed from a varying frequency to the fixed resonance frequency. A graphical example of this is shown in Figure 8. The upper panel shows the waveform of a rock-music excerpt; the thin curve depicts its envelope. The middle and lower panels show the spectrograms of the corresponding input and output signals of the non-linear pre-processing. It is clearly seen that the frequency bandwidth of the signal around 60 Hz is reduced by the pre-processsing, but the temporal modulations remain the same.

## Discussion

Sound reproduction with small loudspeakers in small cabinets is not efficient at low frequencies. This leads to the designer's dilemma: high efficiency or a small enclosure? To meet the demand for a certain cut-off frequency, the enclosure volume must be larger. Alternatively, the efficiency for a given

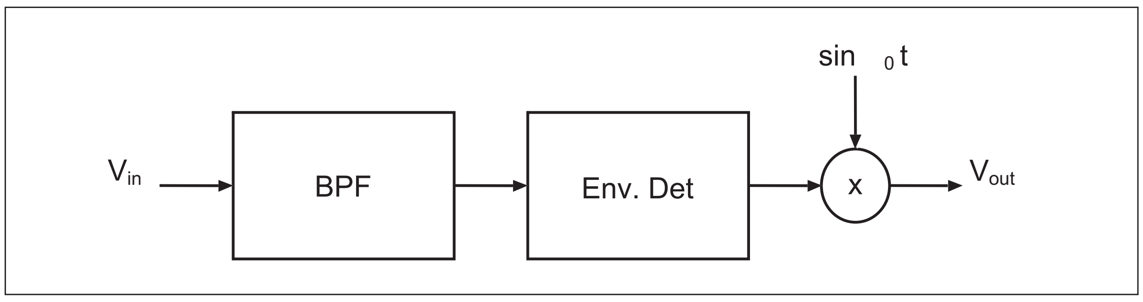


*Figure 7 Signal pre-processing scheme for frequency mapping. The box labeled BPF is a band pass filter, EnvDet is an envelope detector and the multiplier functions as an amplitude modulator. The output signal $V_{out}$ is fed to the loudspeaker via a power amplifier.*

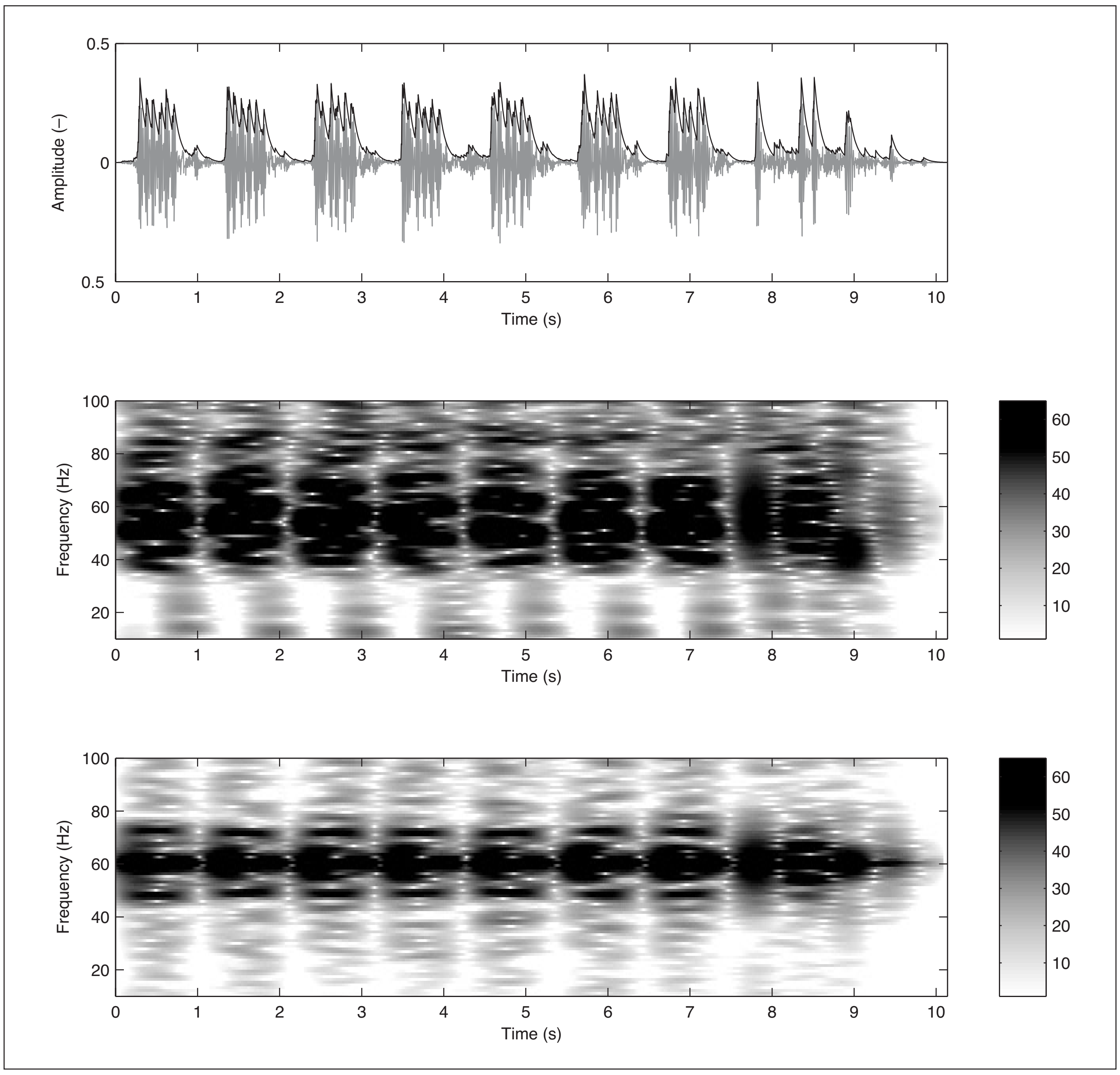


*Figure 8 The signals before and after the signal processing of Figure 7. The upper panel shows the . input signal $V_{in}$ of BPF as a function of time; additionally, the thin curve represents the output signal of the envelope detector. The middle and lower panels, show the spectrograms of the $V_{in}$ and $V_{out}$, respectively.*

volume will be less than for a system with a higher cut-off frequency.

For a number of cases, we have now solved this dilemma by using the low-*Bl* concept at the expense of a somewhat decreased sound quality and the need for additional electronics to accomplish the required frequency mapping by means of non-linear signal pre-processing.

While the resulting new type of loudspeaker is not HiFi, many informal listening tests and demonstrations have confirmed that the decrease of sound quality is only modest; most probably, because the auditory system is less sensitive at low frequencies. Also, the other parts of the audio spectrum have a distracting influence on this mapping effect, which has been confirmed during formal listening tests (Ref.5), where the detectability of mis-tuned fundamental frequencies was determined for a variety of realistic complex signals. Finally, the part of the spectrum which is affected is limited to the 20-to-120-Hz frequency range. The higher harmonics of these low tones lie mainly outside this range and are therefore not affected. They will contribute in their normal un-processed fashion to the well-known missing-fundamental effect.

All these factors support the notion that detuning due to the preprocessing becomes difficult to perceive once the target complex is embedded in a spectrally and temporally *rich* sound context, as is typical for applications in modern multimedia reproduction devices (Ref.5).

As a final remark, we would like to mention that the graphical results of Figs. 2 up to 5 have actually been derived from our experimental loudspeaker MM3, depicted in Figure 6.

## Conclusions

The force factor *Bl* plays a very important role in loudspeaker design. It determines to a large degree the efficiency, the sensitivity, the impedance, the SPL response, the weight and the cost. It does not appear possible to obtain simultaneously both a high efficiency and a high sensitivity over a wide frequency range. At the loudspeaker's resonance frequency, however, it appears to be possible to meet these criteria. The sensitivity is optimal when the electrical damping force is equal to the mechanical one, while it is only 3 dB less efficient than an infinite-force-factor loudspeaker. A new low-*Bl* loudspeaker has been developed, which together with some additional electronics yields a low-cost, light-weight, compact, physically flat, optimally sensitive, and very highly efficient loudspeaker system for low-frequency sound reproduction. For a more strictly mathematical derivation of the results presented in the present paper we refer to Ref.3.

## Acknowledgments

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**Look harder at the stats**

Complaints about noise at East Midland's Airport appear to be soaring: 4500 in 2005 up to 8000 in 2006, not far short of doubling. But, in fact, 60% of all those complaints come from just five people.