Audio Engineering Society

Convention Paper 7346

Presented at the 124th Convention
2008 May 17–20 Amsterdam, The Netherlands

Perception and physical behavior of loudspeaker nonlinearities at bass frequencies in closed vs. reflex enclosures

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ABSTRACT

This paper examines loudspeaker nonlinearities at bass frequencies in closed and reflex enclosures using signal analysis and perceptual evaluation methods. The nonlinearities are investigated by driving the loudspeakers to be compared with sinusoidal and musical test tones. The produced responses are evaluated in terms of diaphragm displacement, harmonic distortion, and bandwise distortion. In addition, a listening experiment is conducted in order to determine how the nonlinearities are perceived in both reflex and closed enclosures. The results show that with signals that have energy close to the tuning frequency of the reflex port produce more distortion with the closed enclosure. On the other hand, acoustic bass test tone behaved in an opposite way causing more distortion with the reflex enclosure. These phenomena were verified with the listening tests.

1. INTRODUCTION

A major challenge in loudspeaker design is to minimize the effect of nonlinearities, while reaching the target frequency response specifications. Hence, knowledge of the behavior of nonlinearities is important in loudspeaker design. Particularly, it is important to know how the nonlinearities are perceived by typical listeners. In this paper, the effect of loudspeaker nonlinearities at bass frequencies is examined both from objective and subjective viewpoints. The investigation is extended to include both reflex and closed enclosures, which are known to have different nonlinear characteristics.

Much research has already been done on the behavior of loudspeaker nonlinearities. Reviews on the subject have been written by Klippel [1], Cabot [2], Czerwinski et al. [3], and Voishvillo [4]. Schmitt has investigated the audibility of nonlinear distortion by using nonlinear models [5, 6]. Moreover, Tan et al. [7, 8, 9, 10] have proposed a signal analysis method in order to evaluate the audibility of distortion. Geddes and Lee have suggested similar kind of method for analyzing the audibility of static nonlinearity [11, 12].

In this work, the topic is approached by producing both sinusoidal and musical test tones by using two reference loudspeakers: a loudspeaker with reflex enclosure and a closed-box loudspeaker. The closed enclosure is modified from the reflex loudspeaker by closing the reflex port. The effect of loudspeaker nonlinearities is evaluated in three ways. First, the distortion in the radiated sound is evaluated with signal analysis methods. Second, the displacement of the cone is analyzed. Third, listening experiments are conducted in order to analyze the perception of the effect.

This paper is organized as follows. The basics of loudspeaker nonlinearities are discussed in Section 2. Then, the reference loudspeakers are introduced in Section 3. The evaluation methods of nonlinearities are presented in Section 4. The results are shown and discussed in Section 5. Finally, the conclusions are drawn in Section 6.

2. LOUDSPEAKER NONLINEARITIES

The passive electro-dynamic driver (Fig. 1) is a transducer between electrical-mechanical and mechanical-acoustical domains converting electrical energy into acoustic energy in a loudspeaker. The voice coil positioned in the air gap of the magnet is connected to the cone, and the current flow in the coil with a magnetic field across the gap generates a force. The mechanical motion of the cone caused by force creates the pressure waves in the air and audible sound. Enclosures with different structures are used to control the backwards radiation of sound from the drivers.

In loudspeakers with dynamic drivers, most nonlinearities occur at high values of amplitude due to the material geometric properties of the components, by the displacement of the voice coil, and by the air flow in the enclosure. Some regular nonlinearities causing distortion are overviewed briefly in this section.

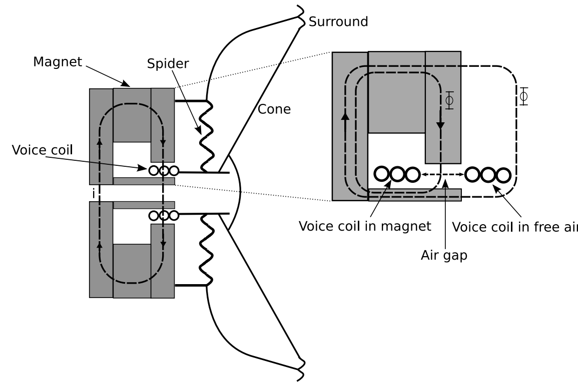

Fig. 1: *Sectional view of the dynamic driver.*

2.1. Nonlinear force factor

The force factor Bl of the magnetic circuit provides coupling between electrical and mechanical domains in the electro-dynamic driver.

The force factor is not constant, but decreases when the voice coil starts to leave the air gap at high values of amplitude. In Fig. 2(a) a force-displacement curve is presented. The curve is flat as long as the coil is positioned in the air gap with small a displacement from equilibrium. If the coil-gap configuration is equal-width, already a small deviation of the coil from the rest position produces nonlinearity. The displacement-dependent force factor can be defined as

$$F = Bl(x)i, \quad (1)$$

where B is the flux density of the magnetic circuit, l is the length of the voice coil wire, x is displacement and i represents current. In addition to the coil-gap configuration, the shape of the force-displacement curve depends also on the flux density B [1].

2.2. Nonlinear suspension

The suspension system, consisting of a spider and surround, provides a restoring force that moves the voice coil back to its equilibrium. A flexible spider is connected to the voice coil and it is used to center the coil in the air gap of the magnet. The suspension system behaves like a spring.

At low values of amplitude, approximately linear relationship between force and displacement occurs, but at high values of amplitude, the force increases nonlinearly caused by the material properties and geometry of the suspension system, and this displacement-dependent nonlinear mechanical stiffness generates distortion. Nonlinear restoring force is defined as

$$F_s = \frac{x}{C_{\mathrm{ms}}(x)}, \tag{2}$$

where $C_{\mathrm{ms}}(x)$ is a nonlinear compliance (the inverse of stiffness, $1/K_{\mathrm{ms}}$). A typical nonlinear compliance C_{ms} as a function of displacement is shown in Fig. 2(b).

2.3. Nonlinear inductance

Current flow in the voice coil generates a magnetic field. When the force factor Bl makes the voice coil to deviate, also the magnetic flux Φ varies depending on the position of the coil. When the coil is placed towards free air outside the gap, the inductance is lower than if the coil would be placed more inside the magnet. The medium has an effect on the magnetic resistance as well as on the electrical input impedance, which is higher inside the magnet than in free air. Magnetic flux depending on the position of the voice coil is computed as

$$\Phi = L(x)i, \tag{3}$$

where L is inductance. An example of nonlinear inductance-displacement curve is presented in Fig. 2(c).

Magnetic flux Φ and inductance L vary nonlinearly also depending on the magnitude of the current. Magnetic flux depending on the current is defined as

$$\Phi \quad = \quad L(i)i. \tag{4}$$

3. THE REFERENCE LOUDSPEAKER

The dynamic driver *SEAS CA18RNX* [14] is used in a reflex enclosure reference loudspeaker in this study. No tweeter is used because we are interested only in low-to-mid frequency behavior. The driver specifications are presented in Table 1. The size of the reflex type enclosure is 12 litres with dimensions: width 23.6 cm, height 34.4 cm, and depth 25.3 cm. The length of the reflex port without flanged ends is 15.76 cm and the diameter is 4.5 cm. Medium density fibreboard (MDF, thickness 22 mm) is used as a wall material in the enclosure, which is filled with damping material. Theoretically, the tuning frequency of the reference loudspeaker should be about 45 Hz.

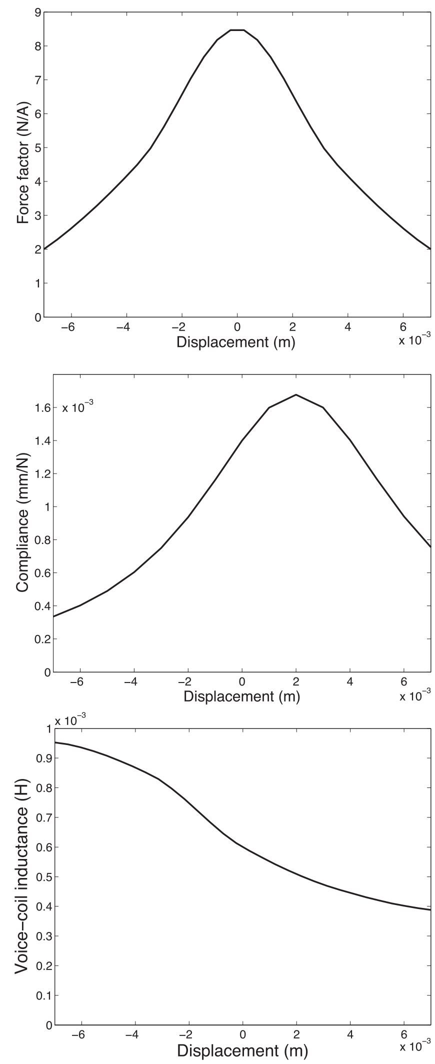

Fig. 2: *Nonlinear a) force factor b) compliance and c) inductance as a function of displacement. Curves have been interpolated using data from [13].*

The measured main-axis frequency responses of the loudspeaker both in closed and ported configurations are shown in Fig. 3. The lower cut-off frequency with open reflex port is about 55 Hz (solid line). The reflex port is closed tightly with stiff material making it a closed-box loudspeaker (dashed line). As is typical for small enclosures, the difference between closed and reflex enclosures is relatively small in the frequency responses. The difference between the closed and reflex enclosure behaviors can be seen

Table 1: SEAS CA18RNX driver

Driver diameter	18 cm
Frequency range	45-3000 Hz
Voice coil height	18 mm
Air gap height	6 mm
Linear coil travel	12 mm
Maximum coil travel	22 mm
Magnetic flux density	1.0 T
Voice coil resistance	6.1 Ω
Voice coil inductance	1.1 mH
Force factor	6.4 N/A
Free air resonance	36 Hz
Suspension compliance	1.6 mm/N
VAS	36 litres
QMS	1.7
QES	0.43
QTS	0.35

more clearly in Fig. 13, where the results for the displacement measurements are shown as a function of frequency.

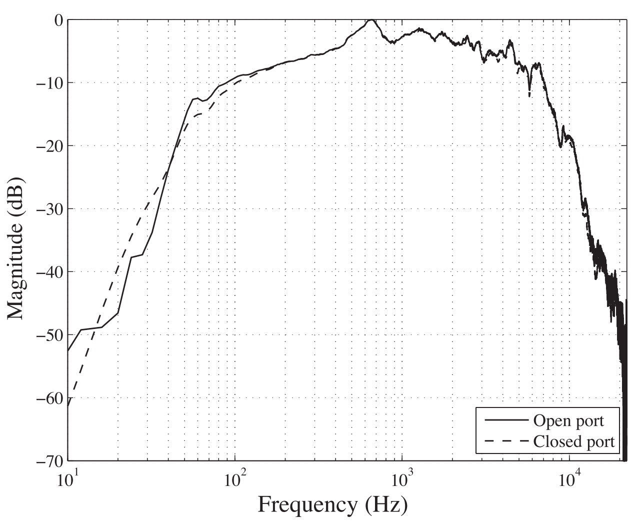

Fig. 3: *Frequency responses for the loudspeaker with open (solid) and closed (dashed) reflex port.*

4. EVALUATION OF NONLINEARITIES

4.1. Production of test tones

In order to evaluate the nonlinear phenomena, a set of test responses were produced using the reference

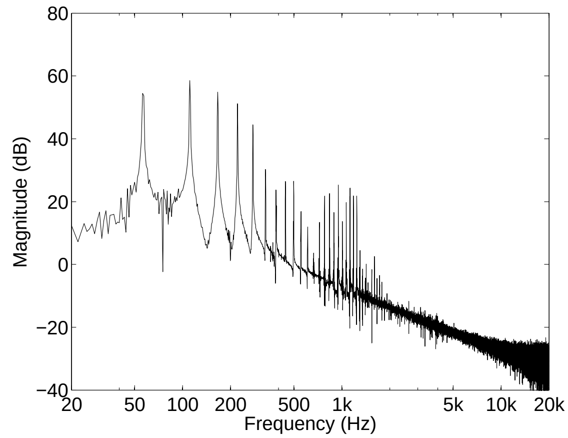

Fig. 4: *Spectrum of the 'ebass' test tone including electric bass and bassdrum sounds.*

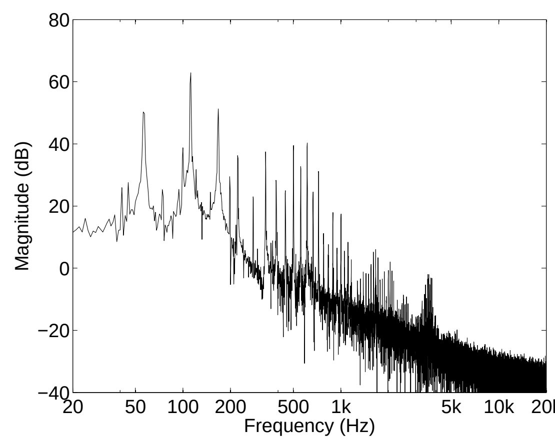

Fig. 5: *Spectrum of the 'abass' acoustic bass test tone.*

loudspeakers. Four different tones were used: a 50 Hz sinusoidal (denoted as 'sine50'), a 114 Hz sinusoidal (denoted as 'sine114'), a combination of electric bass and bass drum tones (denoted as 'ebass'), and a plucked acoustic bass (denoted as 'abass'). The length of the test tones was approximately 1.5 seconds. The 'ebass' test tone was produced with a commercial synthesizer using sampled sounds, while the 'abass' test tone was a recorded tone. Other musical tones with rich bass content were also examined, but it turned out that the phenomena were most audible in these two cases out of the investi-

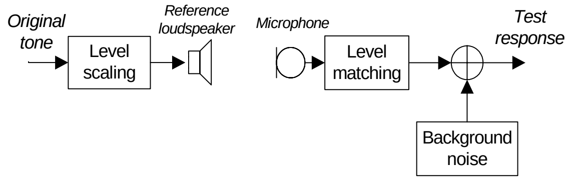

Fig. 6: *Block diagram of the test tone production system.*

gated tones. The spectrum of the 'ebass' tone is shown in Fig. 4 and the spectrum of the 'abass' tone is presented in Fig. 5. The fundamental frequency of the musical test tones was approximately 55 Hz.

Fig. 6 shows the procedure how the test responses were produced. First, the level of the original tone (RMS value of all four tones were set the same) was scaled so that 11 test tones were produced for each original tone with uniformly spaced levels from -20 dB to 0 dB (0 dB is the level of the original tone). Then, the 44 test cases were driven through the reference loudspeakers in an anechoic chamber and recorded with a microphone.

In order to produce test signals for the listening experiment, the RMS levels of all test tones were matched to be equal. The -10 dB test tones were chosen to be the reference signals as the background noise was too disturbing with lower input signal levels. Hence, signals from -10 dB to 0 dB were used in the listening experiment. Since the background noise level is increased as the level is increased in the RMS matching, additional background noise was added to all signals except the reference signals. The additional noise was extracted from a 'sine50' reference signal, where the fundamental frequency was filtered out, and the level of the added noise was matched manually so that it was similar to the noise level of the reference tone.

4.2. Measurement of distortion

The distortion in the test responses without level matching and additional background noise was analyzed with signal analysis methods. The distortion in the sinusoidal test tones can be easily measured by extracting the total harmonic distortion (THD). The determined THD values are shown in Fig. 7 for the 'sine50' tone and in Fig. 8 for the 'sine114' tone

Fig. 7: *Total harmonic distortion of the 50 Hz sinusoidal tone in closed and reflex enclosures. Input level 0 dB is the input level of the original tone.*

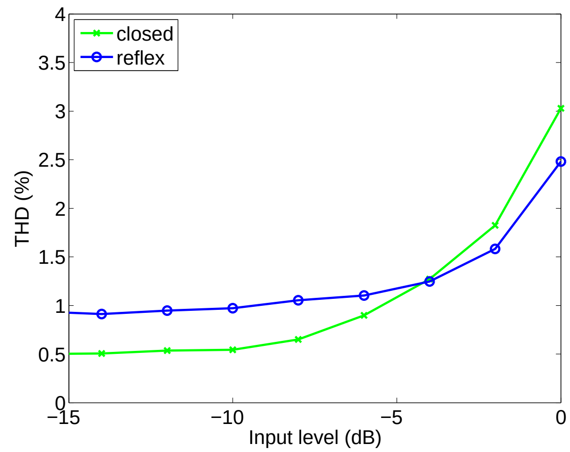

Fig. 8: *Total harmonic distortion of the 114 Hz sinusoidal tone in closed and reflex enclosures. Input level 0 dB is the input level of the original tone.*

as functions of input level. The results show that the THD in 'sine50' is higher than in 'sine114', as expected. Secondly, the closed-box loudspeaker produces more distortion at high signal levels than the reflex loudspeaker.

However, at low signal levels the reflex loudspeaker produces more distortion. The reasons to this were not analyzed in more detail, but one possible explanation might be related to the reflex port that causes additional noise, which can be seen as higher sound levels of the harmonics.

Distortion analysis with musical test tones is a more complicated task, as the effects of distortion cannot be easily seen in the spectrum or in the envelope of the signal. One way of analyzing the distortion is to separate the test tone into 40 ERB bands [8]. Then, the effect of distortion can be seen in the envelopes of the bandlimited signals. Fig. 9 shows an example of the envelopes of a single band with 'ebass' test tone. When the 0 dB test tone envelope is compared to the -10 dB envelope, it can be seen that the 0 dB test tone has some kind of modulation effect in the attack of the tone, which is caused by the distortion. The

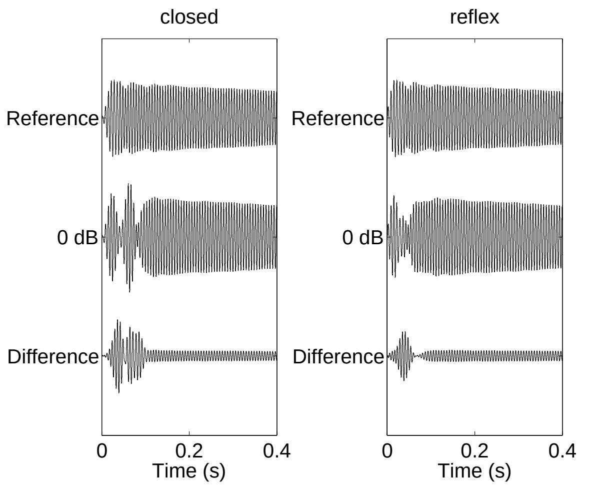

Fig. 9: *Envelopes of the bandlimited (center frequency of the band 199 Hz) 'ebass' test tones in closed (left) and reflex (right) enclosures. The response levels are matched. The bottom envelope is the difference of the reference tone and 0 dB tone envelopes.*

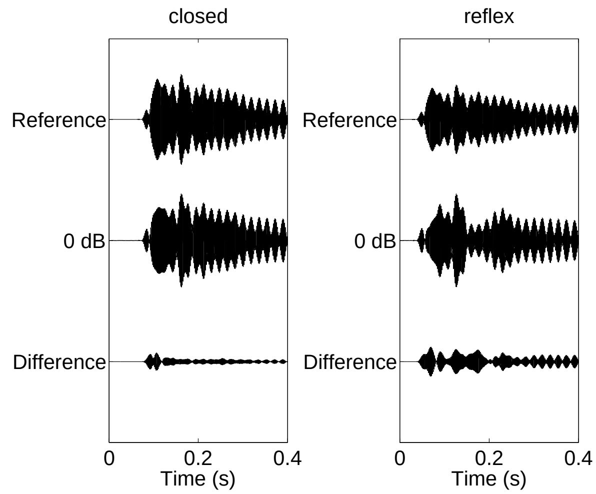

Fig. 10: *Envelopes of the bandlimited (center frequency of the band 649 Hz) 'abass' test tones in closed (left) and reflex (right) enclosures. The response levels are matched. The bottom envelope is the difference of the reference tone and 0 dB tone envelopes.*

same effect is discovered in the difference of the two envelopes. It can be also observed that the distortion effect is greater in the closed enclosure than in the reflex enclosure for the 'ebass' test tone.

Similar results for the 'abass' test tone are presented in Fig. 10. In the contrast to the 'ebass' test tone, the distortion effect in abass test tone is more notable in the reflex enclosure than in the closed enclosure.

Fig. 11 and 12 show the RMS values of the envelope level differences for each frequency band. The results indicate that the distortion effect is greater in the closed-box loudspeaker for the 'ebass' test tone and in the reflex loudspeaker for the 'abass' test tone as previously suggested.

4.3. Displacement measurements

An optical measurement is used to find out the displacement of the cone at different values of amplitude. The displacement of the cone as a function of frequency is measured in the vented enclosure with open and closed reflex port using laser vibrometer (*Polytec OFV 303*, $\lambda = 633$nm). The cone was deviated using logarithmic sinusoidal sweep as test signal. The displacements (peak-to-peak level) were measured at level intervals of 2 dB from 0 dB to -20 dB. The maximum output voltage of the amplifier

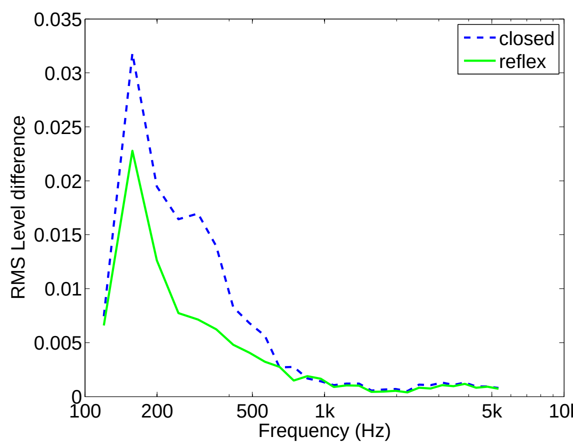

Fig. 11: *RMS level differences at ERB frequency bands for 'ebass' test tone in closed (dashed blue line) and reflex (solid green line) enclosures when envelopes of signals with input levels 0 dB and -10 dB are compared.*

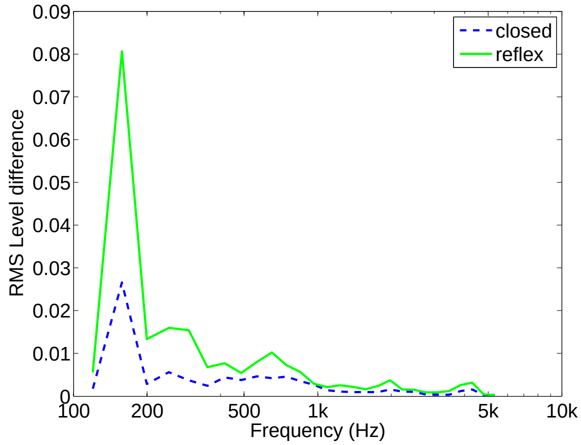

Fig. 12: *RMS level differences at ERB frequency bands for 'abass' and test tone in closed (dashed blue line) and reflex (solid green line) enclosures when envelopes of signals with input levels 0 dB and -10 dB are compared.*

measured with oscilloscope was 23 Volts (peak-to-peak) for 0 dB. Results for optical measurements are shown in Fig. 13.

It can be seen in the displacement-frequency curves that the cone is deviating as expected with open as well as with closed reflex port. With open reflex port at tuning frequency (45 Hz), the displacement is small, and below that frequency, the displacement increases more strongly. Above the tuning frequency (about 45-65 Hz), the displacement starts to increace as a function of frequency, and at still higher frequencies, the displacement decreases. With closed reflex port, the displacement decreases as a function of frequency over the whole frequency range.

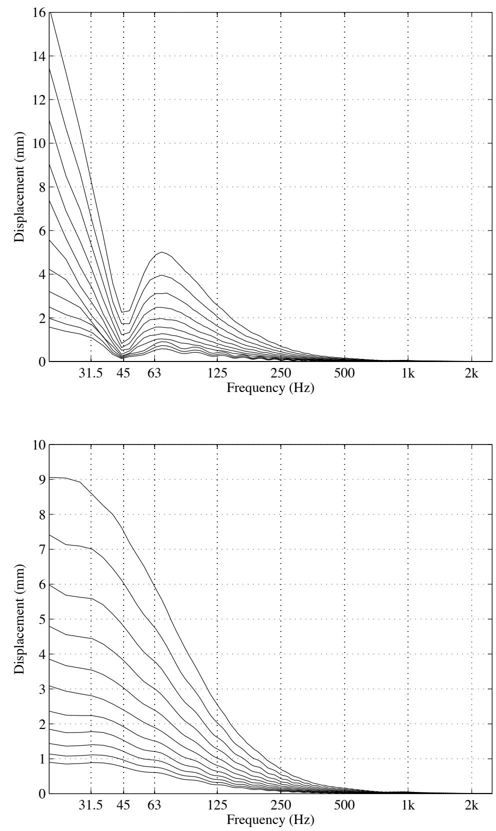

Fig. 13: *Displacement (peak-to-peak level) as a function of frequency with open (upper) and with closed (lower) reflex port.*

4.4. Perceptual evaluation

The effect of distortion was further evaluated by conducting listening experiments. The goal was to determine the limits of audibility for each test tone in both reference loudspeakers. Method of constants was used in the experiment. The sinusoidal test signals were examined in five signal levels (-8 dB to 0 dB) and the musical test signals were investigated in four signal levels (-6 dB to 0 dB) as preliminary tests indicated that it is difficult to detect distortion below -6 dB with the musical test signals. The experiment was conducted with seven test subjects including the authors JR, JA, and MT. Out of the test subjects, one subject produced unreliable results and, hence, his results were not used in the analysis.

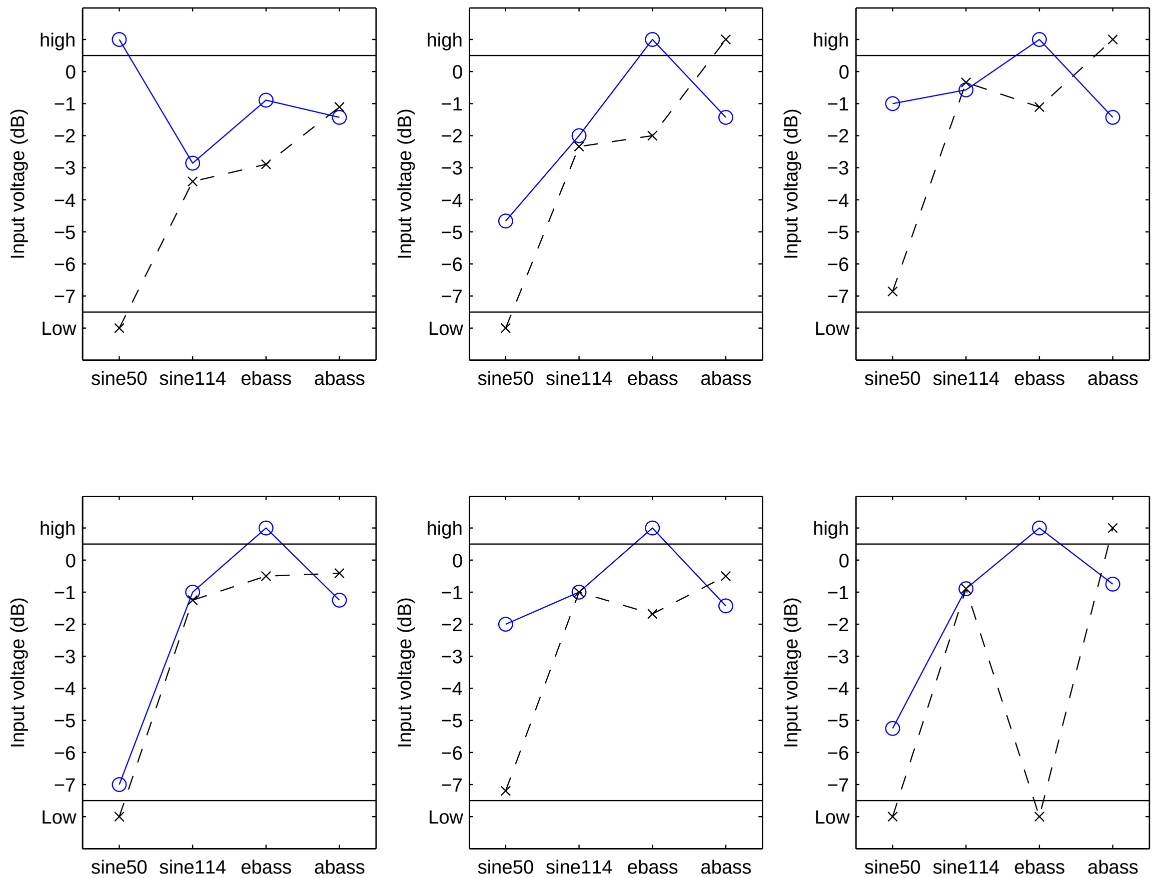

Fig. 14: *Just noticeable distortion level: results from listening experiments with closed (dashed line with crosses) and reflex (solid line with circles) enclosures for individual subjects. If the results in an individual test case are mostly more than 50 % of distortion perceived for all signal levels, the value is denoted as low (below lower horizontal line). Similarly, the value is denoted as high if the results are mostly less than 50 % of distortion perceived (above higher horizontal line).*

The test subjects listened to the test signals with headphones (Sennheiser HD580). To make sure the listening test setup would not add any extra distortion to the sound samples, harmonic distortion of the headphones used in the test was measured. The measurement was performed with a Cortex MK-1 artificial head by playing sinusoids (60, 100, and 440 Hz) from the headphones, and by capturing the signals with the microphones inside the artificial head's ears. The excitation signals were played at SPL of 86 dB, measured at the ear of the artificial head. For 60 Hz and 100 Hz excitations, all harmonic components were below -45 dB, which was the noise floor of the measurement setup at these frequencies. For 440 Hz the harmonic components were below -60 dB. These distortions are low enough not to have effect on the listening test results.

At each test case, the test subject listened to two signals (reference signal and a test signal) in random order. Then, he was asked if he could detect difference in the distortion of the two signals. Distortion was defined in this case as any kind of difference excluding the background noise. Each test case was repeated ten times and the order of all test cases in-

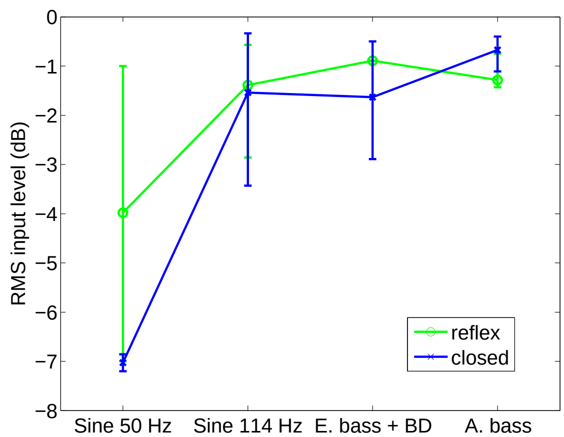

Fig. 15: *Limits of audibility of distortion for the four test tones in closed (blue line with crosses) and reflex (green line with circles) enclosures based on the listening experiments. Notice the large variance of the 'sine50' case.*

cluding repetitions was randomized. The percentage of positive answers (difference perceived) was determined for all signal levels and the obtained psychometric curve was used in determining the threshold of audibility.

Fig. 14 shows the results for each test subject. When the results with closed-box and reflex loudspeakers are compared, three things can be observed. First, the distortion in 'sine50' test tones is more audible in the closed enclosure. Second, the perceived distortion for the 'sine114' test tone is very similar in the reference loudspeakers. Third, the distortion is more easily perceived in closed enclosure for the 'ebass' test tone and in the reflex enclosure for the 'abass' test tone. The average thresholds of audibility are presented in Fig. 15 underlining the previously mentioned statements. The large variance in the results for 'sine50' is due to the background noise that is perceived more strongly against 'sine50' than against 'sine114' due to the properties of human hearing.

The test subjects were asked also to give qualitative feedback on how they perceived the differences in the tones. With the sinusoidal test tones, the dominating feature was sound color. On the other hand, the dominating feature with the musical test tones was the envelope of the tone attack. This is the reason why tones with sharp attack, namely, 'ebass' and 'abass', were selected for this experiment.

5. DISCUSSION AND CONCLUSIONS

The goal of this study was to apply objective and subjective methods in order to deepen the understanding of distortion phenomena in loudspeakers at low frequencies. Rather than carrying out extensive experiments, we wanted to obtain qualitative knowledge on how objective and subjective measures are related. Therefore this was more a methodologically widening exercise than focusing on a specific aspect of distortion.

The results from the distortion measurement and listening experiment show that the closed enclosure produces more distortion than the reflex enclosure in most cases. This is a generally accepted assumption with tones that have a lot of energy around the tuning frequency of the reflex port. However, in the case of 'abass' acoustic bass test tone both the distortion measurement and the listening experiment indicated that the reflex enclosure produced more distortion. This may be understood since this signal has lower level around 50 Hz and higher lever around 100 Hz, as can be seen by comparing Figs. 4 and 5. Fig. 10 also indicates that the reflex box has more problems in attack transient response than the closed box. Thus the generation of nonlinearities depends essentially on the characteristics of signals to be reproduced.

In general the correspondence between objective and subjective measures of nonlinear distortion is good. The methodology applied in this study was found appropriate in finding such correlations, at least on a qualitative level. More extensive studies are needed to deepen the understanding of these behaviors, and finally perceptual/auditory models are needed to combine the physical and psychoacoustic approaches, both of which are needed in successful development of improved loudspeakers.

6. ACKNOWLEDGMENT

This work was partially related to the Academy of Finland research project 106956. Jukka Ahonen has received funding from Fraunhofer Institute for Integrated Circuits. Jukka Rauhala was supported by the Nokia Foundation.

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