

Direct-Radiator Loudspeaker Systems with High Bl *

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In an extension of an earlier paper by the authors additional consequences of a dramatic increase in the motor strength Bl of a driver are shown. Not only is the efficiency of the loudspeaker and amplifier greatly increased, but high Bl values have a positive influence on other aspects of loudspeaker systems. Box volume can be reduced significantly and other parameters can be altered. A prototype driver unit is studied, which performs well in a small sealed box. Vented systems do not benefit as much from high Bl .

0 INTRODUCTION

Direct-radiator loudspeakers typically have a very low efficiency since the acoustic load on the diaphragm or cone is relatively low compared to the mechanical load, and in addition the driving mechanism of a voice coil is quite inefficient in converting electric energy into mechanical motion. The drivers have a magnetic structure that is deliberately kept mediocre so that the typical response is flat enough to use the device without significant equalization.

Some decades ago a new rare-earth-based material, neodymium-iron-boron (NdFeB), in sintered form came into more common use. It has a very high flux density coupled with a high coercive force, possessing a $B-H$ product up by almost an order of magnitude. This allows drivers to be built in practice with much larger total magnetic flux, thereby increasing Bl by a large factor. An earlier paper of the authors has outlined some features of normal sealed-box loudspeakers with greatly increased Bl [1]. That work focused mainly on the efficiency of the system as applied to several amplifier types, but it also indicated several other avenues of interest.

An important conclusion of that earlier work is that a high Bl value causes the loudspeaker to become quite reactive with attendant very high impedance. This means that although somewhat more voltage is necessary for

similar acoustic output, the required current is very much less. For an increase in Bl by a factor of 5, the power taken by the loudspeaker is reduced by more than an order of magnitude, and the amplifier dissipation is approximately halved.

The increased reactive nature of the system can be seen in Fig. 1 [1]. For each Bl value the loudspeaker has been equalized to produce precisely the same acoustic signal. Note that at the higher Bl value the instantaneous power is often negative, as would be expected for a highly reactive system.

It might be expected that the power dissipated in the

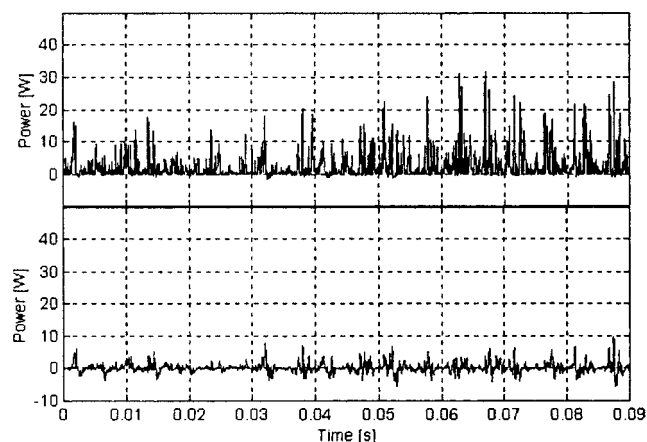


Fig. 1. Instantaneous power in model loudspeaker during a passage of pop music (“kinks”). At higher Bl , system is reactive and power is often negative. Top — $Bl = 8$ N/A; bottom — $Bl = 40$ N/A. (From [1]).

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output devices of a class-B or a class-G amplifier driving such a reactive device would be increased, but in fact the current requirements of the loudspeaker are so much lower that the reverse is true. However, a class-D switching amplifier is even more effective in high- Bl systems, since such amplifiers have the ability to return reactive power to the power supply. Hence class-D amplifiers in conjunction with high- Bl loudspeakers could increase the power efficiency up to a hundredfold compared to normal systems with class-B amplifiers.

This paper is a study using simulation and some experiments of 1) sealed loudspeakers with modified box sizes and driver parameters and 2) vented loudspeakers with dramatically increased Bl values. We focus on the bass and midportion of the loudspeaker frequency range, since this is the region of greatest challenge. A glance at some products available today suggests that at least some of the loudspeaker industry is aware of these ideas. In conversation with industry practitioners we found that much of what we learned is well known to the community, although there has not been much public disclosure.

As Bl is increased we will find that equalization *must* be used. The acoustic efficiency will increase a lot, and much smaller box sizes are possible. Increased cone masses provide interesting characteristics as well. For vented systems of high Bl , the port resonance is ill matched to an overdamped box resonance, making vented systems unsuitable at high Bl .

Earlier work [2] more than a decade ago considered a loudspeaker with a moderately high Bl value, coupled with a class-G amplifier, so that the increased efficiency of the driver complemented the efficiency of the amplifier. The study did not give detailed information on the signal statistics or loudspeaker performance, but dealt mainly with amplifier technology. Even earlier work at Philips [3] dealt extensively with the field of loudspeakers and the relationships between parameters.

1 SEALED-BOX LOUDSPEAKER MODEL

We first reiterate briefly the theory for the sealed loudspeaker as presented in [1], then follow up with the addition of a port to represent a vented system. Although we employed the full complex acoustic radiation impedance for the driver in that earlier paper, at the lower frequencies for which we use the theory this was not really necessary. In what follows we use a driver model with a simple acoustic air load. Beranek [4] shows that for a baffled piston this air load is a mass of air equivalent to $0.85a$ in thickness on each side of a piston of radius a . In fact the air load can exceed this value since most drivers have a support basket which obstructs the flow of air from the back of the cone, forcing it to move through smaller openings. This increases the acceleration of this air, augmenting the acoustic load.

The driver is characterized by a cone or piston of area $S_C = \pi a^2$, a force factor Bl , electric coil resistance R_E , a total moving mass M (which includes the air load), a mechanical damping coefficient b , and a suspension spring constant k_S , defined in terms of the free-air reso-

nance frequency f_0 by

$$k_S = (2\pi f_0)^2 M .$$

The sealed box of volume V_0 has a restoring force on the piston with an equivalent spring constant

$$k_B = \frac{\gamma p_0 S_C^2}{V_0}$$

where $\gamma = 1.4$ for air and p_0 is atmospheric pressure.

The current $i(t)$ taken by the driver when driven with a voltage $v(t)$ is given by equating that voltage source to the ohmic loss and the induced voltage;

$$v(t) = i(t)R_E + Bl \frac{dx_C}{dt}$$

where x_C is the piston displacement. The term $Bl dx_C/dt$ is the voltage induced by the driver piston velocity of motion. We ignore the inductance of the loudspeaker and the effect of the eddy currents induced in the pole structure [5]. For harmonic signals described by $e^{j\omega t}$ the previous equation becomes

$$V(\omega) = I(\omega)R_E + j\omega Bl X_C(\omega) \quad (1)$$

where capitals are used for variables in the frequency domain. The external electromagnetic force $Bl I(\omega)$ is related by Newton's law to the inertial reaction and all the other forces by

$$Bl I(\omega) = (-\omega^2 M + j\omega b + k_S + k_B) X_C(\omega) . \quad (2)$$

By eliminating $I(\omega)$, Eqs. (1) and (2) give a final relationship between $X_C(\omega)$ and $V(\omega)$,

$$X_C(\omega) = \frac{(Bl/R_e)V(\omega)}{-\omega^2 M + j\omega [b + (Bl)^2/R_E] + k_S + k_B} . \quad (3)$$

We use an infinite baffle to mount the piston (2π loading), and in the compact-source regime the far-field acoustic pressure $p(t)$ a distance r away becomes

$$p(t) = \rho S_C \frac{d^2 x_C/dt^2}{2\pi r}$$

proportional to the volume acceleration of the source [4], [6]. In the frequency domain we have

$$P(\omega) = -\omega^2 \rho S_C \frac{X_C(\omega)}{2\pi r} . \quad (4)$$

The compact source regime, in which $a \ll \lambda/2\pi$, does not apply at higher frequencies, and the loudspeaker starts to beam acoustic radiation. We choose to extend Eq. (4) to apply over the whole frequency domain. In this way a mass-controlled model gives a nominally flat response over the whole audio band. In reality we would at high frequencies cross over the system to a midrange or tweeter

driver, but we do not discuss this here.

Substituting Eq. (3) into Eq. (4) we get the usual frequency response $H(\omega) = P(\omega)/V(\omega)$,

$$H(\omega) = \frac{-\omega^2 \rho (S_C/2\pi r) Bl/R_E}{-\omega^2 M + j\omega [b + (Bl)^2/R_E] + k_S + k_B}. \quad (5)$$

Eqs. (2) and (3) can be solved for the current $I(\omega)$ in terms of $V(\omega)$, the voltage input to the loudspeaker. This driving voltage is usually supplied by an amplifier of low output impedance. The electrical impedance of the loudspeaker can be calculated as $Z(\omega) = V(\omega)/I(\omega)$,

$$Z(\omega) = \frac{R_E \left\{ -\omega^2 M + j\omega [b + (Bl)^2/R_E] + k_S + k_B \right\}}{-\omega^2 M + j\omega b + k_S + k_B}. \quad (6)$$

Note that as Bl increases, the damping term $(Bl)^2/R_E$ dominates the behavior. For large Bl , $Z(\omega)$ will be reactive, with phase very close to $+90^\circ$ or -90° . The inverse of the impedance, the admittance $Y(\omega) = I(\omega)/V(\omega)$, can be used to calculate the current waveform when audio signals are applied to the loudspeaker. We refer the reader to [1] which gives plots of $H(\omega)$ and $Z(\omega)$ together with an analysis of the large increase in efficiency when Bl is increased.

2 SEALED-BOX CALCULATIONS AND EXPERIMENT

Fig. 2 shows two frequency responses of the model loudspeaker using Eq. (5) with the following parameters, which are typical of an 8-in (20-cm) loudspeaker having a voice-coil diameter of about 2 cm

$$\begin{aligned} M &= 0.015 \text{ kg (total moving mass)} \\ a &= 0.08 \text{ m} \\ m_A &= 0.00328 \text{ kg (acoustic air load)} \\ Bl &= 8.0 \text{ N/A} \\ R_E &= 6.0 \Omega \end{aligned}$$

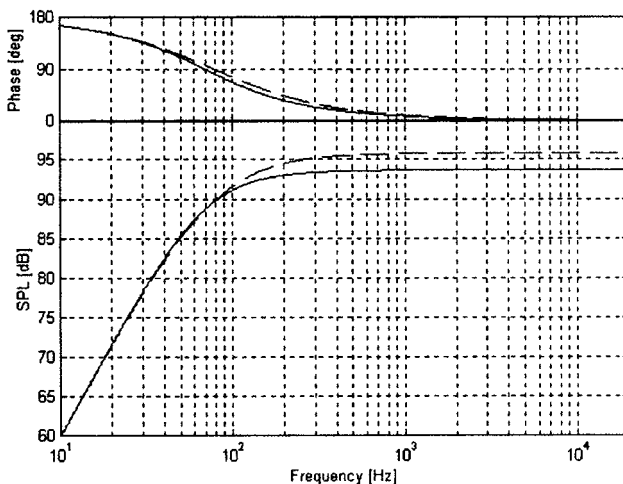


Fig. 2. Frequency response of loudspeaker model for $Bl = 8.0$ N/A. — response including acoustic air load; - - - response without acoustic load. Air load near baffled piston makes significant difference in response.

$$\begin{aligned} f_0 &= 30.0 \text{ Hz} \\ b &= 1.0 \text{ N}\cdot\text{s/m} \\ V_0 &= 0.025 \text{ m}^3 \\ r &= 1.0 \text{ m.} \end{aligned}$$

The curves show the effect of the air load on a driver. The thin solid line is the response when the air load m_A of 3.28 g is not included. The air load has decreased the response by about 2 dB due to the added mass. The damping is determined largely by Bl and partly by b , and has been chosen to give an approximate Butterworth high-pass characteristic so that there is no peak in the bass.

For these responses the input voltage to the loudspeaker is $\sqrt{8}$ volts and the output sound pressure is normalized to 2×10^{-5} Pa, so the curves give the sound pressure level (SPL) at 1 m for 1 W into a nominal 8- Ω load. We have used an infinite baffle to mount the transducer (2π loading), so the response will be down by 6 dB if the unit is mounted away from any boundaries (4π loading). This would reduce the sensitivity of the system to about 87 dB SPL, a value typical for the parameters listed. Other parameters are atmospheric pressure $p_0 = 1.013 \times 10^5$ Pa, speed of sound $c = 343$ m/s, adiabatic constant $\gamma = 1.40$, and density of air $\rho = 1.20$ kg/m³.

3 EFFECT OF HIGH Bl

Fig. 3 shows the frequency response curves [Eq. (5)] for two Bl values, 8 N/A and 40 N/A. At the higher Bl value the electromagnetic damping is very high. If we ignore the small mechanical acoustic damping of the driver, the damping is proportional to $(Bl)^2/R_E$. For a Butterworth response the inertial term $\omega^2 M$, damping $\omega (Bl)^2/R_E$, and total spring constant $k_S + k_D$ are all about the same at the bass cutoff frequency. When Bl is increased by a factor of 5, the damping is increased by a factor of 25. Thus the inertial factor, which must dominate at high frequencies, becomes equal to the damping at a frequency about 25 times higher than the original cutoff frequency. This causes the flat response of the system to have a 6-dB per octave rolloff below that frequency, as shown in the figure.

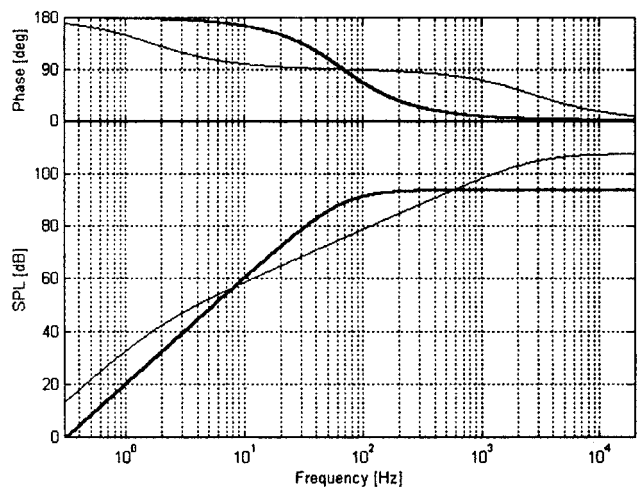


Fig. 3. Frequency response curves of loudspeaker model. — $Bl = 8.0$ N/A; - - - $Bl = 40.0$ N/A.

At very low frequencies the spring restoring force becomes important relative to the damping force at a frequency 25 times lower than the original cutoff frequency. Below this, Fig. 3 shows that the rolloff is 12 dB per octave. Such frequencies are too low to influence audio performance, but it is clear that the box is now no longer constraining the low-frequency performance. We could use a much smaller box without serious consequences.

How much smaller can the box be? The low-frequency break point has been moved down by a factor of nearly 25. The suspension stiffness k_s is small, and since $k_B \propto (1/vol)$, the break point will return to the initial bass cutoff frequency when the box size is reduced by a factor of about 25. Our 25-L box could be reduced to 1 L. This appealing aspect of high Bl is shown in Fig. 4. The thin curve shows the break point between the 12- and 6-dB per octave slopes at about 40 Hz. The smaller box has increased this frequency from very low values. Powerful electrodynamic damping has allowed the box to be reduced in volume without sacrificing the response to audio frequencies. The only penalty is that we must apply some equalization.

The equalization needed to restore the response to the

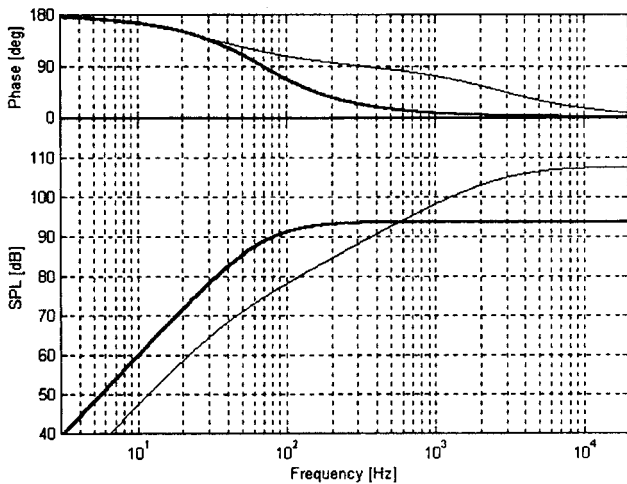


Fig. 4. Frequency response curves of loudspeaker model. — box size 25 L, $Bl = 8.0$ N/A; — box size 1.0 L, $Bl = 40.0$ N/A. High Bl value allows use of very small boxes.

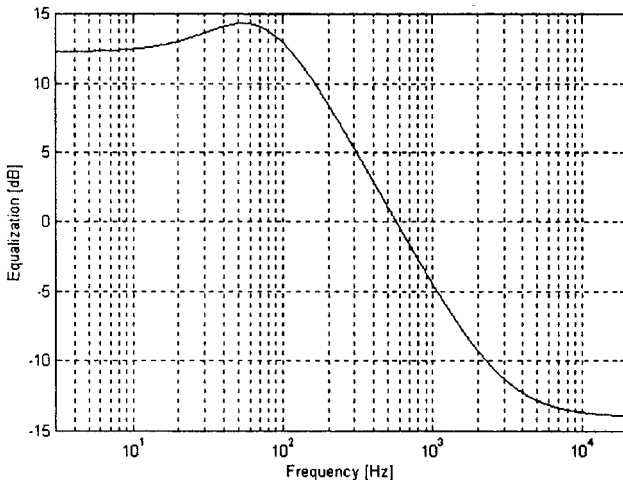


Fig. 5. Equalization needed to restore response to original value after changing box size from 25 to 1.0 L and increasing Bl from 8.0 to 40.0 N/A.

original value is shown in Fig. 5. The slope is close to 6 dB per octave. The break-point geometry of Fig. 4 shows that this results in a curve that has essentially a Bl ratio of 5 (+14 dB) increase at the original cutoff frequency, but reducing at high frequencies to an attenuation of 5 (-14 dB). Such equalization will in virtually all cases increase the voltage excursion applied to the loudspeaker, as shown in [1], since the audio energy resides principally at lower frequencies. The curve levels out at just over 12 dB at low frequencies, but in actual use one might attenuate frequencies below, say, 40 Hz.

The example mentioned is perhaps far too optimistic. It would be very difficult to change Bl by a factor of 5 without a total redesign of the driver. But changes by a factor of 2 are reasonable and could be made by changing the parameters of the magnet and pole structure, without much change in cone mass or other characteristics. Fig. 6 shows the output of a system whose 25-L box has been reduced by a factor of 4 to 6.25 L while the Bl is doubled.

Note that the break point of the system between 6- and 12-dB per octave output slope is at a frequency of about 50 Hz. The box spring is thus not limiting the bass, but of course equalization must still be applied, as shown in Fig. 7. Again, the equalization could be reduced below, say, 40 Hz.

The foregoing ideas cannot be tested readily since drivers must be found that will exhibit the characteristics we have outlined. We found several drivers with high Bl that corroborate some of our conclusions, and one of them is discussed here. This unit is a 10-in (25-cm) nominal bass/midrange driver prototype for a professional sound reinforcement system. It has a total moving mass of 56 g, a cone diameter of 21 cm, free-air resonance of 41.4 Hz, a dc resistance of 7.5 Ω , and a Bl of 22 N/A. The magnet is made of normal ferrite.

The relative damping (discussed in Section 7) for this driver is 4.43, which is 3.13 times that for a nominal Butterworth unit aligned to 41.4 Hz. In free air the impedance has a maximum of 540 Ω . This alone indicates a high Bl value and/or low suspension damping, as can be seen from Eq. (6), since the impedance magnitude will be $R_E +$

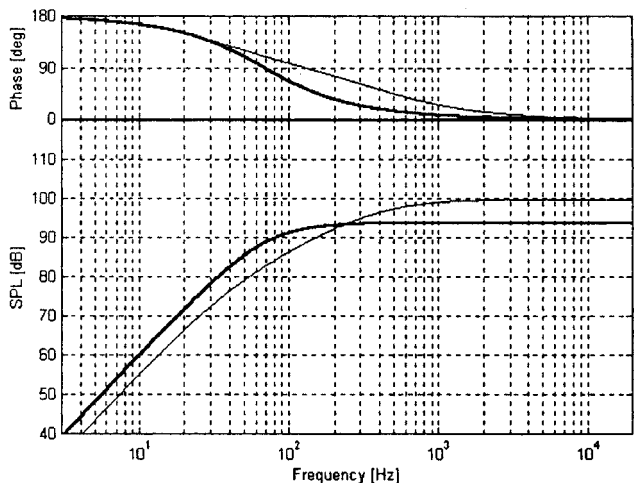


Fig. 6. Frequency response curves of loudspeaker model. — box size 25 L, $Bl = 8$ N/A; — box size 6.25 L, $Bl = 16$ N/A.

$(Bl)^2/b$ at resonance. The unit has a mass of 8 kg. Its magnet structure is 19 cm in diameter and the top plate is 1.2 cm thick. The driver is illustrated in Fig. 8.

Fig. 9 shows the near-field response of this driver in two different situations. The upper curve is the response at the dust-cap of the unit when mounted in a baffle. This ensures a normal air load, which will be similar to that existing when the unit is mounted in a box. The lower curve is the near-field response when the driver is mounted in a 9-L box. This box seems ridiculously small given the size and weight of the driver, but we shall see that it is appropriate.

Although the measured resonance frequency on the box is 83 Hz, the output is down by 3 dB from the baffled response only below 30 Hz. The strong magnet structure makes the response at low frequencies rise at 6 dB per octave, which must of course be equalized out. At higher frequencies the effects of cone breakup and other resonances are visible.

To see what would happen if Bl were decreased, we could place a resistor in series with the loudspeaker in

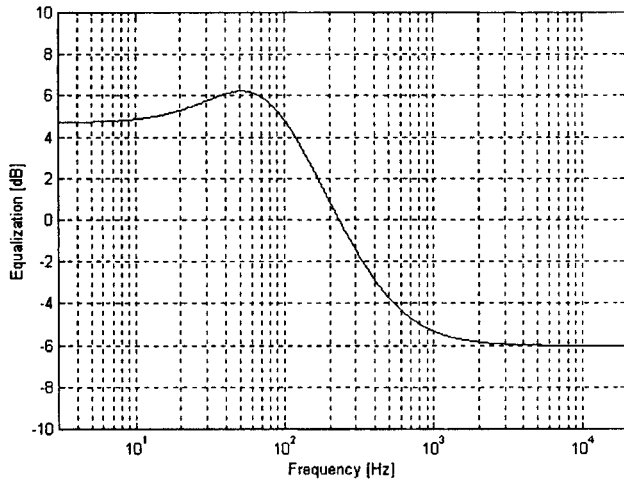


Fig. 7. Equalization needed to restore response to original value after changing box size from 25 to 6.25 L and increasing the Bl from 8 to 16 N/A.

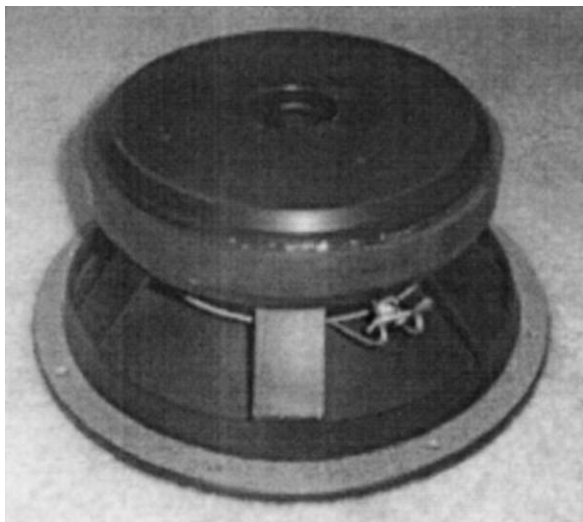


Fig. 8. High- Bl driver. Device is 25 cm and massive magnet structure 19 cm in diameter.

order to reduce the $(Bl)^2/R_E$ damping term. Fig. 10 shows the effect of measuring the loudspeaker, mounted in the 9-L box, but with a 10- Ω series resistor. This reduces the effective damping by a factor of $7.5/(7.5 + 10)$. Note that the response diminishes rapidly just below 80 Hz, which is the resonance frequency on the box. With this increased resonance frequency, the actual damping is just a bit below a Butterworth alignment, as our theory predicts. Thus the system now displays a slightly underdamped response.

4 AN OBSERVATION ABOUT EQUALIZATION

In [1] and for the earlier sections of this paper we calculated the required equalization by calculating the frequency response ratio $H_L(\omega)/H_H(\omega)$ using Eq. (5), where the subscripts refer to the high and low values of Bl . The required equalization function for two loudspeakers with different Bl values, but identical in other respects, can also be calculated using an alternative approach, that gives new insight.

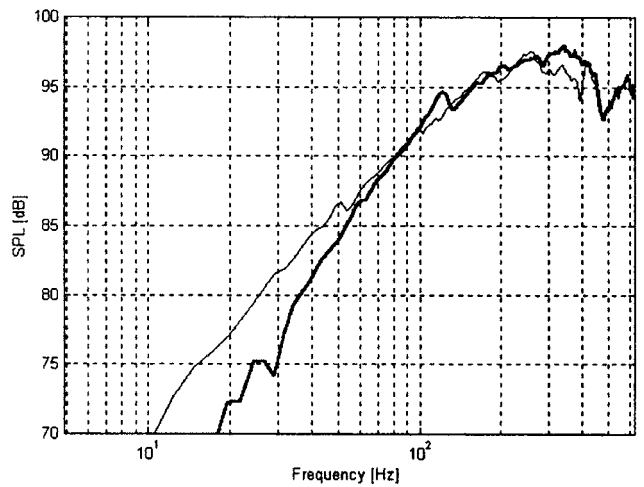


Fig. 9. Near-field frequency response of high- Bl prototype driver unit. Reference response: — when mounted in baffle; — when mounted in 9-L box. High damping reduces low-frequency reduction from such a small box.

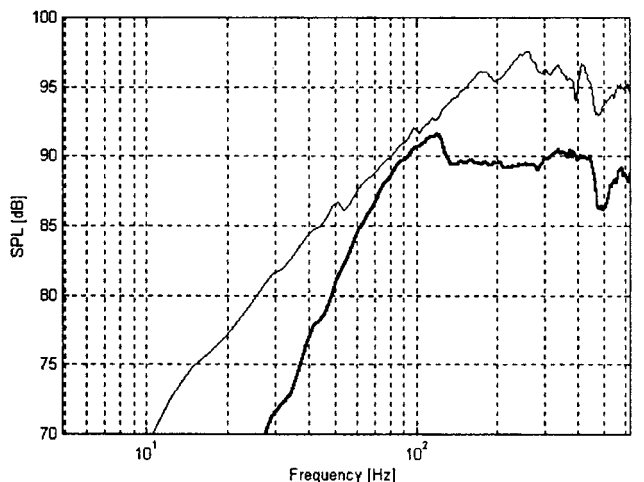


Fig. 10. Near-field frequency response of high- Bl prototype driver unit. Reference response: — when mounted in baffle; — when mounted in 9-L box and measured with 10- Ω series resistor. Damping is reduced by a factor of 2.3, and now the 83-Hz box resonance frequency reduces the response by 12 dB per octave below that.

For our two loudspeakers to produce the same acoustic output, the shape and motion of the two pistons or cones must be the same. Since all other aspects of the loudspeakers are the same, this can be achieved if the total force on the pistons is the same, thus ensuring that they have the same motion. The instigating force is derived from the electromagnetic Lorentz force, $Bl I(\omega)$. If this force is the same in the two cases, then the responding forces such as the pressure inside the box, the acoustic radiated pressure, and other mechanical forces will be the same. Thus the total piston force will be the same.

Since the current $I(\omega) = V(\omega)/Z(\omega)$, where $V(\omega)$ is the loudspeaker voltage and $Z(\omega)$ its electrical impedance, we must make arrangements so that $BlV(\omega)/Z(\omega)$ is the same for the two conditions. Hence,

$$\frac{Bl_H V_H(\omega)}{Z_H(\omega)} = \frac{Bl_L V_L(\omega)}{Z_L(\omega)} .$$

Note, however, that since

$$H_{EQ}(\omega) = \frac{V_H(\omega)}{V_L(\omega)}$$

then

$$H_{EQ}(\omega) = \frac{Bl_L/Z_L(\omega)}{Bl_H/Z_H(\omega)} \tag{7}$$

a very simple relationship that indicates the importance of the electrical impedance in determining loudspeaker characteristics. We can verify the result from Eqs. (5) and (6). Note that it applies for the response at any orientation, not just on axis, and represents a general property of acoustic transducers with magnetic drive.

5 VENTED-BOX LOUDSPEAKER MODEL

To model the vented or ported loudspeaker we consider the driver mounted in a box that has a port with its opening nearby on the baffle. This model has been studied long ago by Thiele [7] and Small [8]. Here we use a physical approach with explicit driver and other acoustic parameters.

A port of area S_p and length L has a mass of air $m = \rho LS_p$, and we think of this plug of air as moving in response to the pressure inside the box. The displacement $x_p(t)$ of this air causes a change in pressure inside the box, which causes a force on the piston. The motion of the piston and the air in the port are thus coupled by the spring resulting from the air in the box.

When we apply Newton's law $Ma = \Sigma F$ to the piston, including the external electromagnetic force $Bl I(\omega)$, the inertial force and all the other forces are related by

$$-\omega^2 M X_C(\omega) = -j\omega b X_C(\omega) - (k_S + k_B) X_C(\omega) - k_B \left(S_P / S_C \right) X_P(\omega) + Bl I(\omega) . \tag{8}$$

The second line contains the force on the piston caused by the motion of the air in the port. It is convenient to use the spring constant of the box k_B for the piston, normalized by the port-to-piston area ratio, to represent this force.

By eliminating $I(\omega)$ from Eqs. (1) and (8) the final relationship between $X_C(\omega)$, $X_P(\omega)$, and $V(\omega)$ is

$$\begin{aligned} & \left\{ -\omega^2 M + j\omega \left[b + \frac{(Bl)^2}{R_E} \right] + k_S + k_B \right\} X_C(\omega) \\ & + k_B \frac{S_P}{S_C} X_P(\omega) \\ & = N_1(\omega) X_C(\omega) + k_B \frac{S_P}{S_C} X_P(\omega) \\ & = \frac{BlV(\omega)}{R_B} . \end{aligned} \tag{9}$$

$N_1(\omega)$ represents the quadratic factor in ω in braces and has the dimensions of a spring constant. It is positive at low frequencies. Note that the factor $j\omega(Bl)^2/R_E$ is the electromagnetic damping. It is usually much higher than the damping due to the acoustic impedance (which we have neglected) or the damping coefficient b .

The acceleration of the air mass m in the port is related by Newton's law to the total pressure in the box, which in turn relates to the displacements of both piston and port, and the port damping coefficient β ,

$$\begin{aligned} -\omega^2 m X_P(\omega) & = p_{Box} S_P \\ & = \frac{\gamma P_0}{V_0} (-S_C X_C - S_P X_P) S_P - j\omega \beta X_P(\omega) . \end{aligned}$$

Solving for X_C gives

$$\begin{aligned} X_C(\omega) & = \left[\frac{(\omega^2 m - j\omega \beta) V_0}{\gamma P_0 S_P S_C} - \frac{S_P}{S_C} \right] X_P(\omega) \\ & = N_2(\omega) X_P(\omega) . \end{aligned} \tag{10}$$

$N_2(\omega)$ is also a quadratic resonance factor in ω , and it is dimensionless. This term is negative at low frequencies, meaning that the motion of the cone and the air in the port is in antiphase, as we would expect. β is usually very small and the port resonance is then essentially undamped, with $X_P(\omega)$ being very large relative to $X_C(\omega)$ near the resonance frequency given by

$$\omega^2 = \frac{\gamma P_0 S_P^2}{m V_0} .$$

There will, however, be some damping due to coupling with the cone assembly. If the port is replaced by a passive radiator, Eq. (10) must be augmented by subtracting its suspension spring constant in the bracket containing the mass m and damping β .

By substituting Eq. (10) into Eq. (9) we can obtain a

result for either $X_C(\omega)$ or $X_P(\omega)$. If we choose to eliminate $X_P(\omega)$ we get

$$\left[N_1(\omega) + \frac{k_B S_P}{S_C N_2(\omega)} \right] X_C(\omega) = Bl \frac{V(\omega)}{R_E} \quad (11)$$

while eliminating $X_C(\omega)$ gives

$$\left[N_1(\omega) N_2(\omega) + k_B \frac{S_P}{S_C} \right] X_P(\omega) = Bl \frac{V(\omega)}{R_E}. \quad (12)$$

Rather than expanding Eqs. (11) and (12) to display all the terms, we will use the definitions of $N_1(\omega)$ and $N_2(\omega)$ in MATLAB¹ to work out $X_C(\omega)$ and $X_P(\omega)$ from these equations. To appreciate the nature of these responses we can study the ω behavior of the resulting equations.

In Eq. (11) the term in square brackets containing N_1 and N_2 will be fourth order in ω in the numerator and second order in the denominator, including a constant term. Hence $X_C(\omega)$, proportional to the reciprocal of that term, is also a fourth-order response, low pass in nature, but asymptotically having a second-order rolloff $1/f^2$ at high frequencies. This is reasonable since the piston inertia will dominate at high frequencies. At low frequencies the response will be noninverting, as would be expected for the forced motion of a simple spring, described by the suspension spring constant k_S .

The term in square brackets in Eq. (12) is quartic in ω . Thus $X_P(\omega)$ is a fourth-order low-pass response. The response at low frequencies is inverting, as would be expected since slow motion of the piston will cause air-flow in the port in the opposite direction. At the highest frequencies the piston response goes as $1/f^2$. This is the driving force for the air in the port, whose inertia will make its response fall by another factor $1/f^2$, leading to a $1/f^4$ factor.

As earlier, we use an infinite baffle (2π loading) to mount the piston and the port, and in the compact-source regime the far-field acoustic pressure $p_V(t)$ a distance r away is proportional to the sum of the volume acceleration [6] from the piston and the port,

$$p_V(t) = \rho \frac{S_C (d^2 x_C / dt^2) + S_P (d^2 x_P / dt^2)}{2\pi r}.$$

In the frequency domain we have

$$P_V(\omega) = -\omega^2 \rho \frac{S_C X_C(\omega) + S_P X_P(\omega)}{2\pi r}. \quad (13)$$

By substituting for $X_C(\omega)$ and $X_P(\omega)$ in terms of $V(\omega)$ in Eq. (13), we get the usual frequency response for the vented system,

$$H_V(\omega) = \frac{P_V(\omega)}{V(\omega)}. \quad (14)$$

The motion of the air in a port occurs mainly near the loudspeaker resonance frequency. At this low frequency the imaginary part of the acoustic impedance is dominant, representing an extra mass added to the mass of the air in the port. This can be absorbed into the port length L , which is the physical length of the port plus end corrections. For a flanged end we add $0.85r$ to the length, and $0.613r$ for an unflanged end [4], where r is the port radius. Thus even a port consisting of a round hole in a thin baffle (flanged both ends) has a length of $1.70r$.

6 VENTED-BOX NUMERICAL CALCULATIONS

Many loudspeaker systems use ports or passive radiators to increase the response near the resonance frequency of the box. Does a high Bl value have a beneficial effect for a driver with a port? Fig. 11 shows frequency responses of our earlier sealed model loudspeaker, but now compared to a system with an added port, having the following length and area parameters;

$$\begin{aligned} Bl &= 8.0 \text{ N/A} \\ L &= 0.1 \text{ m} \\ S_P &= 0.00125 \text{ m}^2. \end{aligned}$$

Properly designed vented loudspeakers have approximately a fourth-order Butterworth high-pass response.

Although somewhat unrealistic, to demonstrate clearly the effects with a port, we will consider a change in Bl by a factor of 5. Fig. 12 shows the frequency response curves for the vented loudspeaker for two Bl values, 8.0 and 40 N/A. At the higher Bl value the electromagnetic damping is very high. As for the sealed-box loudspeaker, a properly designed vented loudspeaker also has inertial term $\omega^2 M$, damping $\omega(Bl)^2/R_E$, and total spring constant $k_S + k_D$, all about the same at the bass cutoff frequency. Again an increase in Bl by a factor of 5 results in break points for the inertial factor, which move up in frequency by a factor of 25, and a spring factor break point 25 times lower than

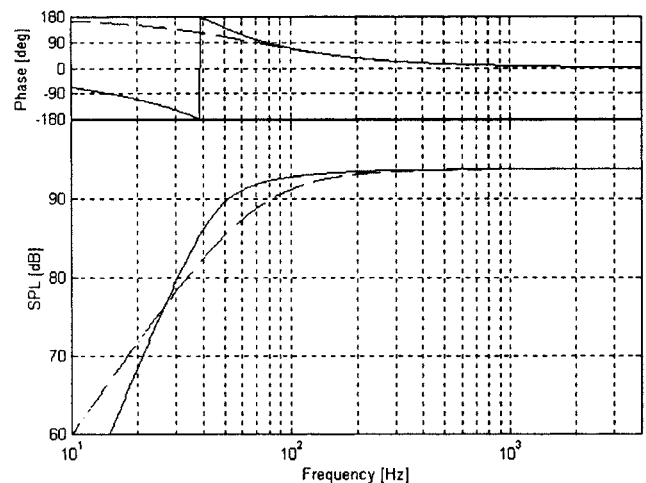


Fig. 11. Frequency response of vented loudspeaker model for $Bl = 8.0$ N/A (—), together with a sealed-box loudspeaker having similar parameters (---). At low frequencies vented system has a fourth-order rolloff whereas sealed system has a second-order rolloff.

¹MATLAB is a trademark of MathWorks, Inc., and this software is readily available.

the original frequency. Below this, the rolloff is 12 dB per octave, as shown. These latter frequencies are too low to influence audio performance.

However, the resonance of the port on the box does not scale with Bl . Also, a higher Bl heavily damps the cone, thereby decreasing the damping of the port resonance. This resonance is quite sharp; its peak reaches about 100 dB. Thus the equalization that is required, shown in Fig. 13, will be quite impractical. Any small change in resonance caused by temperature or port variations would misalign the physical system and the electronic equalization.

The port damping is actually decreased by a high Bl , since the cone is now virtually clamped by the electromagnetic braking. This makes the equalization very dependent on the precise resonance frequency of the port. Note that precisely at the port resonance, the required equalization has the same value as at very high and low frequencies. This is true because the cone has almost no output at these frequencies.

To avoid the very sharp port resonance, we might choose to damp the air motion in the port by introducing a flow resistance, for example, by placing a specific fabric

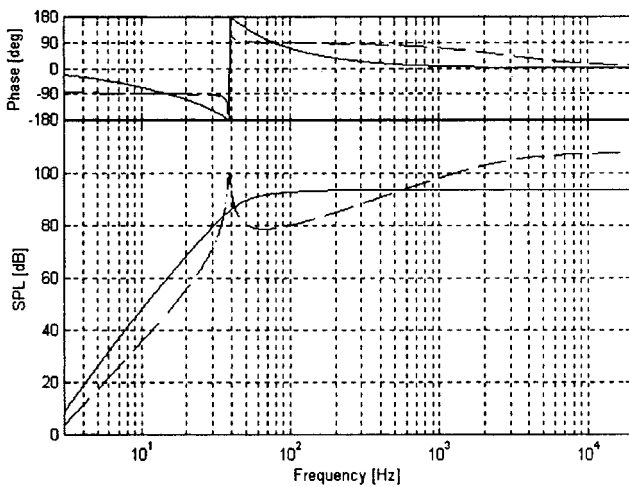


Fig. 12. Frequency response curves of vented loudspeaker model. — $Bl = 8.0$ N/A; --- $Bl = 40.0$ N/A. At high Bl port resonance is almost undamped.

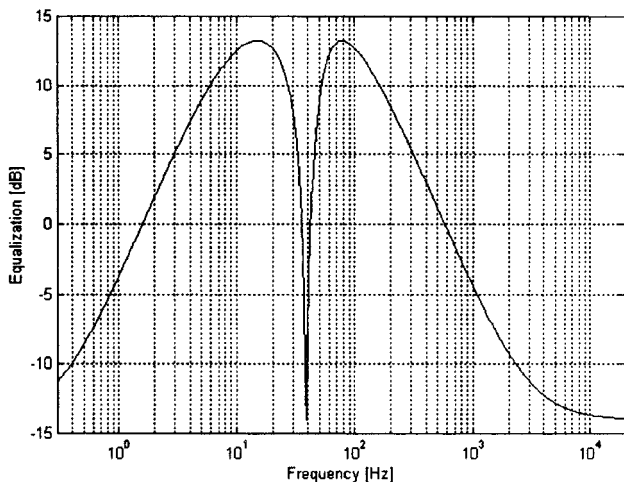


Fig. 13. Equalization needed to restore response to original value after increasing Bl from 8.0 to 40.0 N/A. Port resonance becomes very sharp at high Bl .

material across the port entrance. Fig. 14 shows the effect of a small port damping coefficient of 0.01. This has little effect on the normal $Bl = 8$ case, since the coupling of the port to the cone via the box air spring damps the port resonance much more than the added damping.

The equalization required when modest port damping is employed is shown in Fig. 15. This is a tolerable curve to implement and will not be so affected by parameter variations. Although we do not show it, lower Bl values also prevent the port resonance from becoming too narrow.

When a high Bl value is used, we have seen how sealed loudspeakers can employ much smaller boxes. This is not really possible with vented systems, since small boxes will require very long ports having small areas in order to resonate at frequencies around 50 Hz, and such ports will exhibit viscous air losses and nonlinearity. Passive radiators would not be lossy and their use with high Bl might be feasible.

Whether a port is useful when Bl is significantly increased is left to the reader to judge. There is some

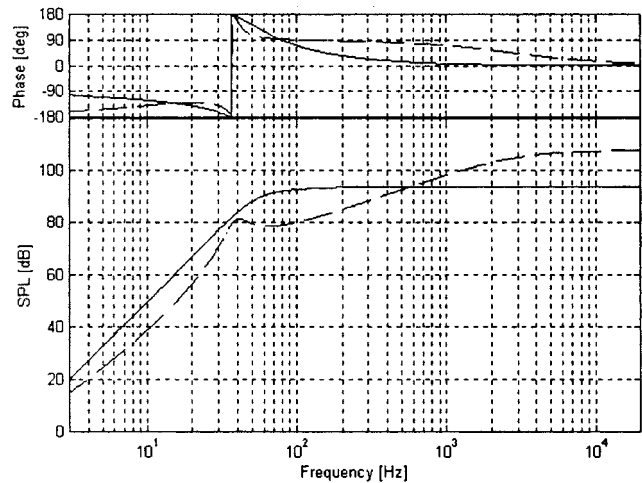


Fig. 14. Frequency response curves of vented loudspeaker model. — $Bl = 8.0$ N/A; --- $Bl = 40.0$ N/A. Port damping coefficient 0.01. This damps the port resonance somewhat, making equalization less troublesome.

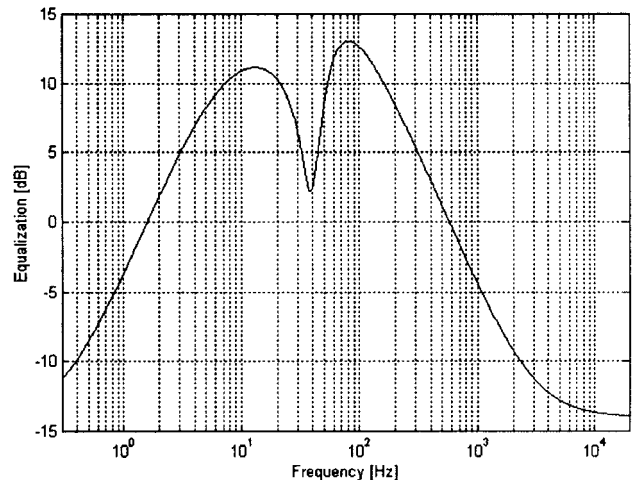


Fig. 15. Equalization needed (after introducing modest port damping) to restore response to original value after increasing Bl from 8.0 to 40.0 N/A. Alignment problems are reduced since port resonance is wider.

enhancement of the lowest frequencies, but the problem of alignment, the extra excursion caused by infrasonic inputs, and the possible requirement of a rather unusual damping speak against this approach. A moderate increase in Bl may still leave the port having some beneficial effect.

7 A DIMENSIONLESS MEASURE OF DAMPING

What would be a good dimensionless parameter to describe the relative damping due to Bl ? As Bl increases, the box and suspension restoring force become less relevant, as we shall see. So we choose a parameter of the form

$$\frac{j\omega (Bl)^2 / R_E}{-\omega^2 M}$$

which is the ratio of the electrical damping force to the inertial force on the total mass M representing the cone with its air load. The unit imaginary and the negative sign should be removed, so the relative damping factor δ becomes

$$\delta = \frac{(Bl)^2}{\omega_0 MR_E} \quad (15)$$

The frequency ω_0 can be chosen to represent the low-frequency end of the intended audio spectrum, or it could be set to a reference frequency such as 50 Hz. The latter may be useful since the low-frequency cutoff of a system is significantly altered when Bl is significantly increased. Incidentally, for the usual Butterworth system aligned to the frequency ω_0 , δ would be $\sqrt{2}$. The driver studied in Section 3 has $\delta = 4.43$.

The common parameter Q_E , the electrical Q factor, while similar to $1/\delta$, is predicated on a normal driver for which the resonance frequency is the interaction between inertial and suspension forces. As Bl is increased, the suspension forces are less relevant, and Eq. (15) is a better measure.

8 OTHER ASPECTS OF HIGH Bl

Our earlier study with reduced box sizes displayed excellent bass characteristics due to the high Bl and appropriate equalization. The cone inertial mass term has a break point with the damping at very high frequencies, such as several kilohertz. What would happen if we increased the mass of the cone in order to force the break point frequency back to normal?

Fig. 16 shows two responses, both with a high $Bl = 40$ N/A and a very small box size of 1.0 L. The heavy curve is for a normal total moving mass of 15 g. The box spring constant has a break point to the damping slope at about 50 Hz, and the inertial term has a break point to the damping slope at about 3 kHz. When the moving mass is increased 25 times to 375 g, the break points line up at about 50 Hz, and the output shown in the light curve is nominally flat and would not require equalization.

Is the system useful? It can act as a bass system without any added equalization, but the sensitivity has been greatly

reduced over much of the band. The impedance now is not high as might be expected from a high Bl , but it is normal, allowing more dissipation and showing a nominal peak near the resonance frequency. Thus although the box is small, this approach seems limited in its usefulness. However, there may be other combinations of box size, Bl , and cone mass which would give useful characteristics.

9 SUMMARY

When the magnetic field strength of a loudspeaker transducer is increased significantly, the system becomes reactive and much more efficient. Greatly increased electrodynamic damping causes the effects of the box to be felt only at frequencies far below the normal bass cutoff. Hence the box volume can be reduced greatly. The resulting system still needs equalization, but has very appealing characteristics.

If the cone mass is increased, the system avoids the need for equalization, but other less attractive features follow.

When a vented system is considered with a driver of high Bl , it displays a very underdamped port resonance. This may necessitate real port damping, negating some of the advantages of the high Bl . If the box size is also reduced, the port geometry becomes troublesome and the port will display viscous losses.

10 ACKNOWLEDGMENT

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11 REFERENCES

[1] J. Vanderkooy and P. M. Boers, "High-Efficiency Direct-Radiator Loudspeaker Systems," presented at the

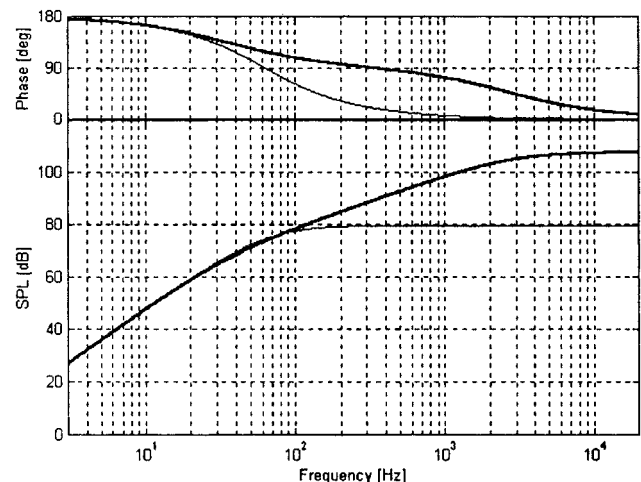


Fig. 16. Frequency response curves of sealed-box systems with high $Bl = 40$ N/A and small box of 1-L volume. — normal moving mass of 15 g; — heavy cone of 375 g.

113th Convention of the Audio Engineering Society, *J. Audio Eng. Soc. (Abstracts)*, vol. 50, p. 957 (2002 Nov.), preprint 5651.

[2] V. A. J. Frowijn, "Height-Efficiency Loudspeaker Systems," Tech. Note 129/86, Philips Research Labs, Eindhoven, The Netherlands (1986).

[3] A. J. M. Kaizer and J. A. M. Nieuwendijk, "The Efficiency of Electrodynamical Loudspeakers," Tech. Rep. 5907, Philips Research Labs, Eindhoven, The Netherlands (1983).

[4] L. L. Beranek, *Acoustics* (McGraw-Hill, New York, 1954); reprinted by American Institute of Physics, New York (1986).

[5] J. Vanderkooy, "A Model of Loudspeaker Driver Impedance Incorporating Eddy Currents in the Pole Structure," *J. Audio Eng. Soc.*, vol. 37 pp. 119–128 (1989 Mar.).

[6] P. M. Morse and K. U. Ingard, *Theoretical Acoustics* (McGraw-Hill, New York, 1968); reprinted by Princeton University Press, Princeton, NJ (1986).

[7] A. N. Thiele "Loudspeakers in Vented Boxes: Parts I and II," *J. Audio Eng. Soc.*, vol. 19 pp. 382–392 (1971 May); pp. 471–483 (1971 June).

[8] R. H. Small, "Direct-Radiator Loudspeaker System Analysis," *J. Audio Eng. Soc.*, vol. 20, pp. 383–395 (1972 June).

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John Vanderkooy was born on January 1, 1943, in Maasland, The Netherlands. He emigrated to Canada with his family at an early age. He received all of his education in Canada, with a B. Eng. degree in engineering physics in 1963 and a Ph.D. degree in physics in 1967, both from McMaster University in Hamilton, Ontario. After a two-year postdoctoral appointment at the University of Cambridge, Cambridge, UK, he went to the University of Waterloo. For some years he followed his doctoral interests in high magnetic-field low-temperature physics of metals. His research interests since the late 1970s, however, have been mainly in audio and electroacoustics. He is a professor of physics at the University of Waterloo.

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In 1976 he joined the Speech and Hearing Group at the Institute of Perception Research in Eindhoven, The

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Ronald M. Aarts was born in Amsterdam, The Netherlands in 1956. He received a degree in electrical engineering in 1977 and a Ph.D. degree from the Delft University of Technology, Delft, The Netherlands, in 1994.

In 1977 he joined the Optics Group of Philips Research Laboratories, Eindhoven, The Netherlands, where he was involved in research into servos and signal processing for use in both Video Long Play players and Compact Disc players. In 1984 he joined the Acoustics Group and was engaged in the development of CAD tools and signal processing for loudspeaker systems. In 1994 he became a member of the Digital Signal Processing Group. There he has been engaged in the improvement of sound reproduction by exploiting DSP and psychoacoustical phenomena.

Dr. Aarts has published over one hundred technical papers and reports and is the holder of more than a dozen U.S. patents in his fields. He was a member of the organizing committee and chair for various conventions. He is a senior member of the IEEE, a fellow of the AES, and a member of the Dutch Acoustical Society and the Acoustical Society of America. He is past chair of the Dutch section of the AES.