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Static and Dynamic Measurement of a Magnet-only Loudspeaker

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Summary

A new loudspeaker technology using Magnet-only motors has been presented recently. Unlike the classical electrodynamic loudspeaker, no iron is used in the motor part. The presence of iron in traditional loudspeaker motor is a source of nonlinearities and, as a consequence, deteriorates the reproduced sound quality. According to the theory of Magnet-only motors, the loudspeaker parameters should vary less than in the case of a classical electrodynamic loudspeaker. In this paper, the parameters of a Magnet-only loudspeaker are measured statically and dynamically. The results presented in this paper clarify why a magnet-only loudspeaker improves the quality of the reproduced sound.

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1. Introduction

A new concept of *magnet-only loudspeaker*, proposed few years ago, eliminates some of the non-linearities of the loudspeaker. The term *magnet-only* depicts a magnetic circuit totally made of rare-earth permanent magnets, such as $NdFeB$ magnets. The elimination of iron from transducer motors is first presented in patent [1] and next can be found in [2, 3, 4, 5]. More recently, Remy [6] presented loudspeaker distortion reduction using bonded magnet-only motors. Advantages of such ironless structures have been shortly highlighted in [7] and [8]. Particularly, analytical studies [8, 9, 10] have shown that magnet-only magnetic circuits can lead to constant motor parameters (i.e. constant electrical resistance R_e, electrical inductance L_e and force factor Bl).

In this paper the motor parameters of a magnet-only loudspeaker are measured as a function of displacement and frequency, using two different methods: statically (the voice-coil is displaced statically from its rest position before the measurement) and dynamically (no additional force is applied).

The prototype of magnet-only loudspeaker used in this study is a mid-range speaker, developed by Orkidia Audio. More details about the prototype of this magnet-only loudspeaker under test can be found in [11].

The aim of this paper is to show experimentally the impact of the use of magnet-only circuit on the behavior of motor parameters.

2. Motor Parameters

A classical approach to describe the motor parameters consists on the Thiele-Small [12] model, based on lumped parameters and linear behavior assumptions. In this model, the electromechanical coupling equation can be written in time-domain as

$$u(t) = R_e i(t) + L_e \frac{di(t)}{dt} + Bl \frac{dz(t)}{dt}, \qquad (1)$$

where $u(t)$ is the voltage across the voice-coil, $i(t)$ is the current through the voice-coil and $z(t)$ is the voice-coil displacement.

Nevertheless, the electrodynamic loudspeaker is known to be a nonlinear device [13]. Assuming constant parameters Bl, R_e and L_e in Eq. 1 may cause a significant error in their estimation. The variations of the force factor Bl with displacement are usually the main source of distortion in low frequencies, where the voice-coil exhibits a large excursion. Its variation with current, temperature and frequency may usually be neglected in comparison with the variation with displacement. The resistance R_e varies with temperature [14], frequency [15] and may also vary with current. The inductance term L_e is more complicated

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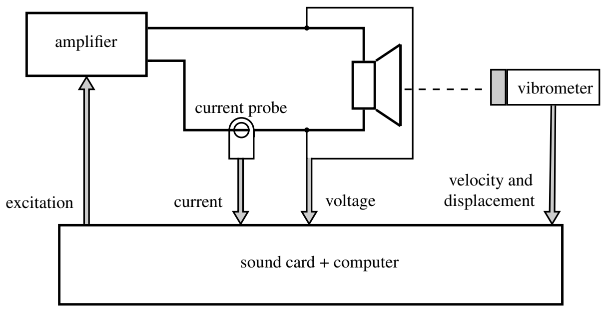

Figure 1. Block schema of the measurement of motor parameters.

due to the presence of eddy currents and due to its dependence on displacement, current, temperature and frequency [13, 16].

In the following, an experimental setup allowing the measurement of the motor parameters and their variations is presented.

3. Experimental Bench

The experimental setup for the measurement of motor parameters is depicted in Fig. 1. The generation and acquisition of signals are carried out by a Sound card RME Fireface 400, with sampling frequency 192 kHz, dynamic range of 110 dB (RMS unweighted) and total harmonic distortion less than 0.001 %. Before driving the loudspeaker, the excitation signal is amplified using Devialet D-Premier amplifier, with signal to noise ratio 130 dB unweighted and total harmonic distortion at full power (240 W) less than 0.001 %. This equipment ensures a high precision measurement.

To measure the current, a Current Probe Fluke i50s with insertion impedance lower than 10 mΩ within the audible bandwidth is used. In addition, a single-point vibrometer Polytec (OFV-503, OFV-505) is used to make non contact measurement of the diaphragm vibrations.

4. Quasi-Static Measurements

In this paper the motor parameters of a magnet-only loudspeaker are measured as a function of displacement and frequency. The static method consists in displacing the voice-coil statically from its rest position either mechanically (the voice-coil is blocked in a given position) or electrically (using a DC-offset to displace the voice-coil from its rest position). Such a method is sometimes called quasi-static.

4.1. Force Factor Measurement

In order to measure the variation of the force factor Bl with voice-coil displacement z, we displace the voice-coil electrically from its rest position using a DC-offset and we drive the loudspeaker with a low level signal, considering a small voice-coil displacement around its steady position z_i. Current $i(t)$ and voltage $u(t)$ are measured using the experimental setup described in the previous section. In addition, the velocity $v(t)$ is measured using a single-point vibrometer allowing the estimation of the force factor Bl [17]. This procedure is repeated for several DC-offsets resulting in several Bl points as a function of the voice coil displacement z_i.

4.2. Resistance and Inductance Measurements

The resistance R_e and the inductance L_e of the voice-coil may vary with several parameters, such as frequency, input current, voice-coil displacement, etc. In order to separate these variations from each other, a different measurement process applied. Adding a DC-offset electrically would influence the measured parameters R_e and L_e and thus a mechanical displacement must be applied.

First, the voice-coil is blocked mechanically in a given position z_i in order to avoid any voice-coil displacement. Thus, $z(t)$ from Eq. (1) is kept $z(t) = z_i$ during the measurement, leading to $\frac{dz(t)}{dt} = 0$. Next, a synchronized swept-sine signal [18] is fed to the loudspeaker and the current $i(t)$ and the voltage $u(t)$ are measured. Before entering the loudspeaker, the swept-sine signal is filtered in a linear way (FIR filter) in order to keep the effective value I_{eff} of the measured current $i(t)$ constant for all frequencies. Next, the voice-coil is blocked mechanically in another position and the procedure is repeated for the same level of I_{eff}.

The electric impedance defined as

$$Z_e(f) = \frac{U(f)}{I(f)}, \tag{2}$$

is calculated for all the measured data. $U(f)$ and $I(f)$ are obtained as the first harmonic product, extracting the higher harmonics[1] using the nonlinear convolution procedure [19]. Resistance R_e and Inductance L_e are then estimated from

$$Z_e(f) = R_e(f) + j2\pi f L_e(f). \tag{3}$$

[1] Note, that neglecting the higher harmonics in order to keep the impedance definition valid (in other words considering that the system under test is linear) is incorrect and may lead to misinterpreting the results. Nevertheless, the goal of this paper is to show that the parameters vary less using the magnet-only motor, in the way they are usually interpreted.

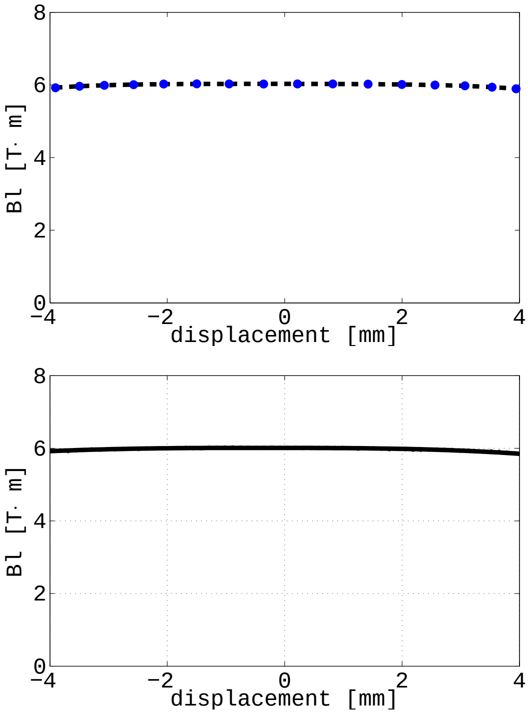

Figure 2. Force factor Bl of the magnet-only loudspeaker as a function of voice-coil displacement (measured data - dots, fit curve - dashed). Static measurement method (above), Dynamic method (below).

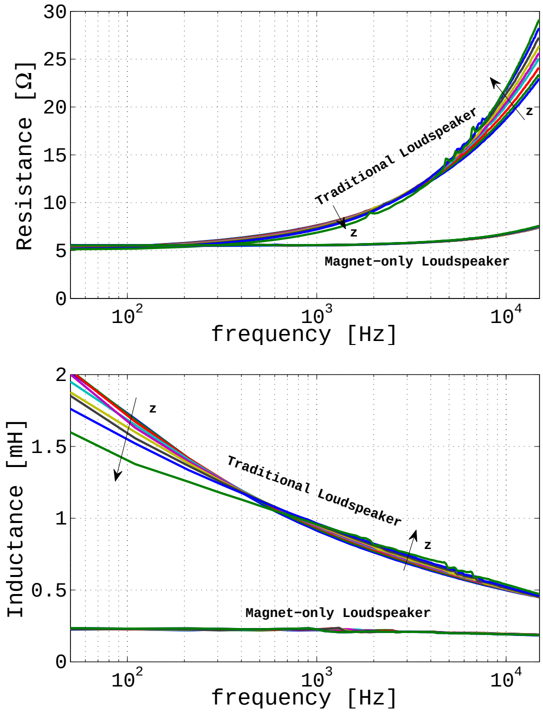

Figure 3. Resistance R_e (above) and inductance L_e (below) as a function of frequency for the traditional and the magnet-only loudspeaker. Results for 9 different blocked voice-coil positions z_i from -4 mm to 4 mm. The effective value of current is kept constant (50 mA).

5. Dynamic Measurements

In order to determine the nonlinear parameters in a dynamic way, the transducer is excited with a multi-tone signal at low frequencies (20 Hz to 200 Hz) in order to obtain large displacements of the diaphragm. The estimation of nonlinear parameters can be accomplished by system identification techniques [20].

6. Results

In this section, we present the results of the static and dynamic measurements of the motor parameters of the magnet-only loudspeaker.

First, the force factor Bl is measured as a function of displacement by dynamic and static method. Next, the resistance R_e and inductance L_e are measured as a function of position using the dynamic measurement and as a function of position and frequency using the static measurement technique.

In order to emphasize the small variations of resistance R_e and inductance L_e in the case of the magnet-only motor, these two parameters are also measured for a traditional loudspeaker whose motor part includes iron. The aim is not to compare the performance of both loudspeakers, but to highlight the different behavior of resistance R_e and inductance L_e due to different principles.

6.1. Force Factor Measurement

Fig. 2 shows the force factor Bl of the magnet-only loudspeaker measured in static manner (above) and dynamic manner (below). The magnet-only loudspeaker exhibits a constant force factor $Bl \simeq 6$ T·m within the whole measured voice-coil displacement region (-4 mm to 4 mm). Both measurement techniques, the static and the dynamic one, give same results.

6.2. Resistance and Inductance Measurement - Static Method

In Fig. 3 resistance R_e (above) and inductance L_e (below) are depicted as a function of frequency for 9 different blocked voice-coil positions z_i from -4 mm to 4 mm. The effective value of current is kept constant at 50 mA.

In order to highlight the different behavior of resistance R_e and inductance L_e due to different structure of loudspeaker motor, the results from a traditional loudspeaker using iron pole pieces is also presented.

In the case of the traditional loudspeaker, the frequency-dependence of both resistance R_e and inductance L_e is significant, whatever the position of the voice-coil in the magnetic circuit. The traditional loudspeaker with iron pole pieces has resistance R_e starting at 5 Ω near the very low frequencies and increasing with frequency up to 25 Ω near 15 kHz.

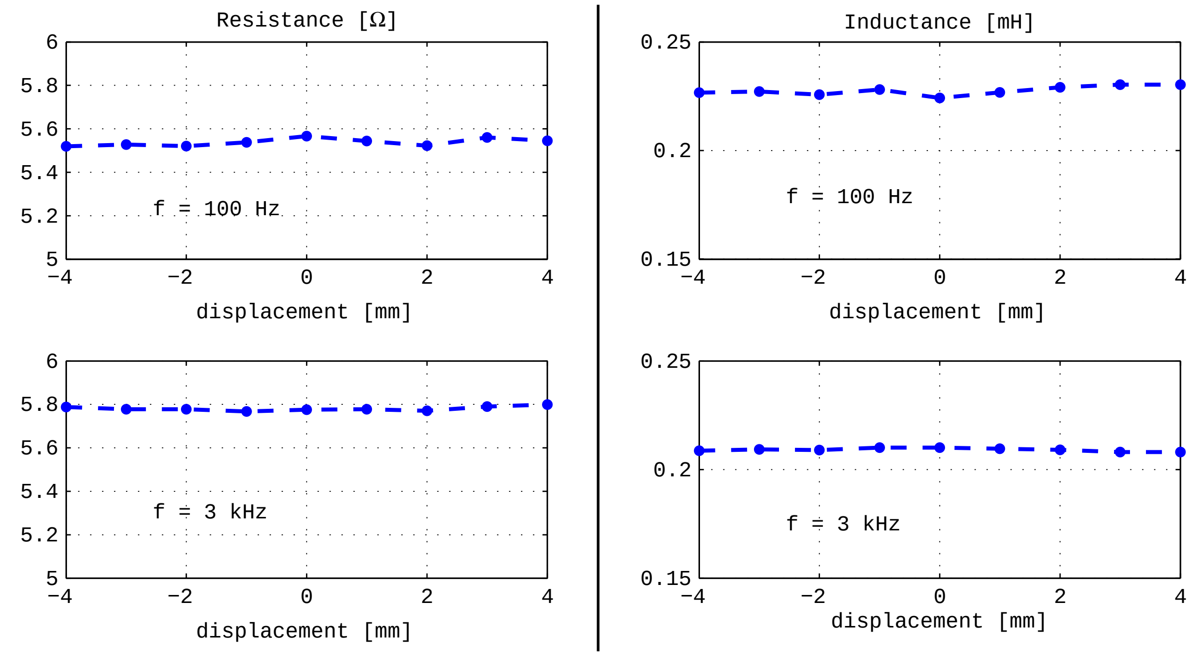

Figure 4. Resistance R_e (left) and inductance L_e (right) as a function of displacement for the magnet-only loudspeaker for two different frequencies f=100 Hz and f=3 kHz. The effective value of current is kept constant (50 mA).

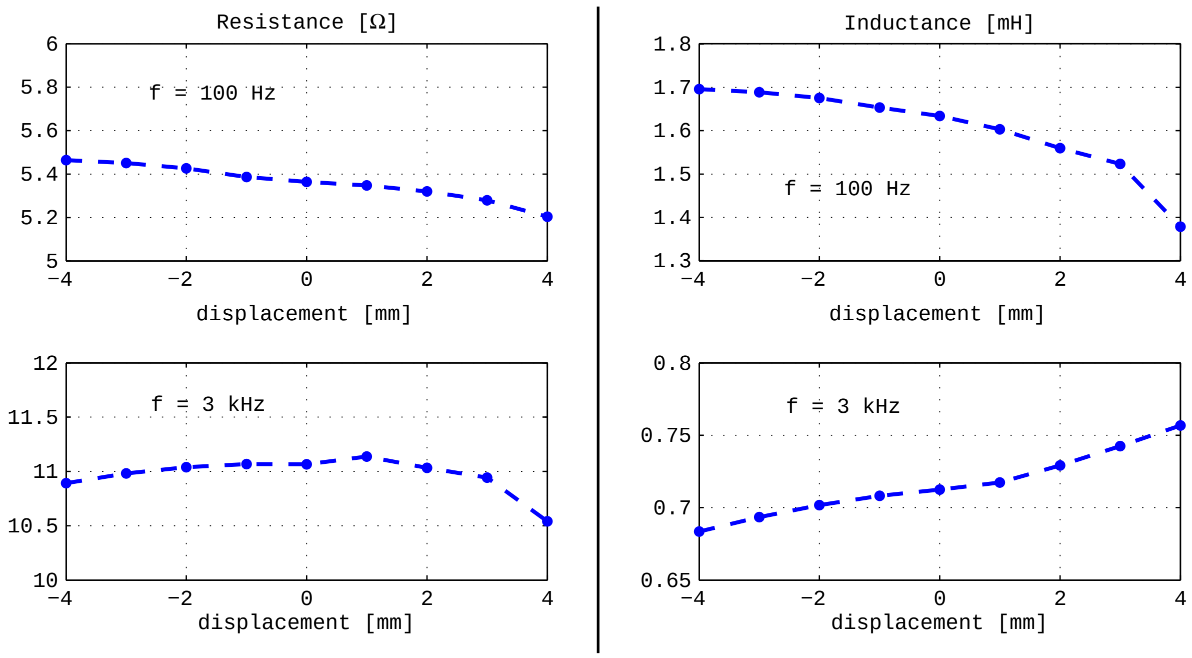

Figure 5. Resistance R_e (left) and inductance L_e (right) as a function of displacement for the traditional loudspeaker for two different frequencies f=100 Hz and f=3 kHz. The effective value of current is kept constant (50 mA).

The inductance L_e decreases from 2 mH at low frequencies to 0.6 mH at high frequencies. This variation of both R_e and L_e in such a large scale (R_e is 5 times higher at high frequencies than at low frequencies, whilst L_e decreases 3 times within the same frequency range) is typical for a traditional electrodynamic loudspeaker due to the eddy currents [15].

The variations of R_e and L_e with frequency, in the case of the magnet-only loudspeaker, is significantly lower, whatever the position of the voice-coil.

Moreover, Fig. 3 reveals a significant dependence of both parameters R_e and L_e on voice-coil displacement in the case of the traditional loudspeaker. Resistance R_e varies with displacement especially at high frequencies, the variation of L_e is more obvious at low frequencies.

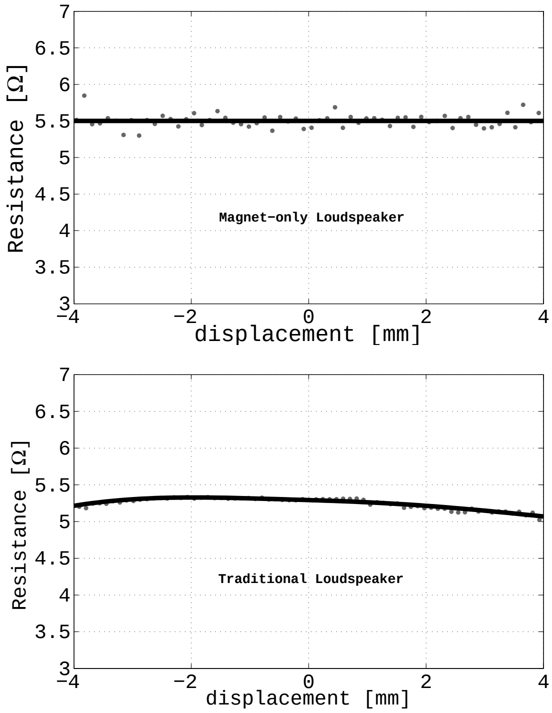

Figure 6. Resistance R_e as a function of displacement measured in a dynamic manner. Magnet-only loudspeaker above, a traditional loudspeaker below.

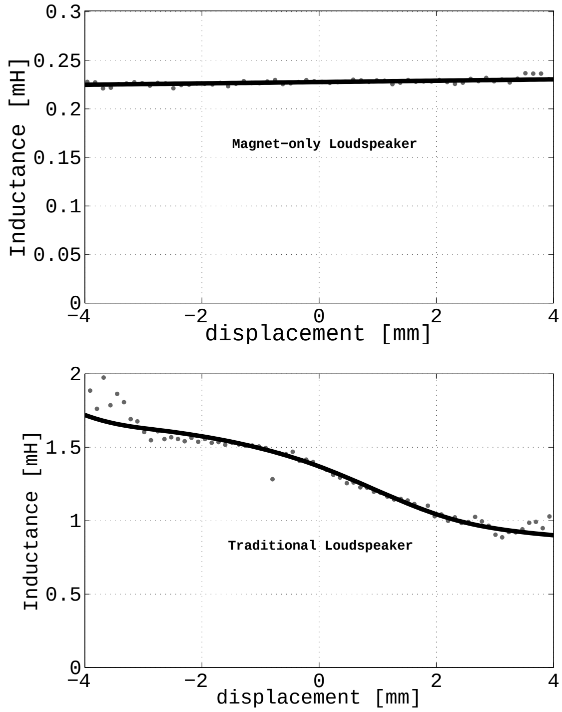

Figure 7. Inductance L_e as a function of displacement measured in a dynamic manner. Magnet-only loudspeaker above, a traditional loudspeaker below.

In Figs. 4 and 5 resistance R_e and inductance L_e are depicted as a function of voice-coil displacement for two arbitrary chosen frequencies 100 Hz and 3 kHz. Almost no dependence on voice-coil displacement can be observed in the case of the magnet-only loudspeaker (Fig. 4). In the case of the traditional loudspeaker (Fig. 5), the variation of both parameters R_e and L_e on displacement is obvious.

At lower frequencies (100 Hz), the inductance L_e is higher when the voice-coil moves towards the motor (z<0) and lower when the voice-coil moves out (z>0), its gradient is negative (Fig. 5). At higher frequencies (3 kHz), the slope of the variation of the inductance L_e with displacement is positive. The inductance L_e is lower when the voice-coil moves towards the motor (z<0) and higher when the voice-coil moves out (z>0). No such effect is observed in the case of the magnet-only loudspeaker (Fig. 4).

6.3. Resistance and Inductance Measurement - Dynamic Method

In Figs. 6 and 7 the variation of resistance R_e and inductance L_e with displacement, measured using the dynamic method, are presented for both types of motors. No variation with displacement is observed in the case of the magnet-only loudspeaker. The inductance L_e of the traditional loudspeaker varies from from 1.7 mH (at -4mm) to 0.9 mH (at 4mm), that is a decrease to almost one-half of its value.

Comparing the variation of traditional loudspeaker inductance L_e obtained from the dynamic method (Fig. 7-below) and from the static method at 100 Hz (Fig. 5), we can see that the variation is more important when measured using the dynamic method.

Nevertheless, the static method shows an important variation of traditional loudspeaker's inductance L_e with frequency (Fig. 3-below), that is not taken into account in the case of a dynamic method. The dynamic measurement method cannot separate the frequency dependence from the dependence on displacement and thus the curves depicted in Figs. 6 and, as such, represents an estimate which is difficult to be interpreted physically.

Since the magnet-only loudspeaker exhibits no variation of resistance R_e and inductance L_e with frequency nor displacement in the frequency range where the dynamic method is used, the results from the static and the dynamic method gives the same values in both cases.

7. Conclusion

The goal of this paper was to verify the theory of magnet-only loudspeakers using static and dynamic measurements. The analytical studies presented lately [8, 9, 10] predict an important increase of linearity due to almost constant motor parameters. A prototype of a magnet-only loudspeaker made by Orkidia Audio has been used for the study.

First, the uniformity of force factor Bl has been shown through both measurement techniques. Next, the variation of resistance R_e and inductance L_e with displacement and frequency using the static method has been presented. In order to stress the small variations of resistance R_e and inductance L_e in the case of the magnet-only motor, these two parameters have also been measured for a traditional loudspeaker whose motor includes iron. This variation of both R_e and L_e with frequency is typical for a traditional electrodynamic loudspeaker due to the presence of eddy currents [15]. The variations of R_e and L_e on displacement may depend on the actual loudspeaker, but they are always observed [13].

In the case of magnet-only loudspeaker a small variation of R_e and L_e with frequency has been observed. All magnet-only motor parameters (force factor Bl, resistance R_e and inductance L_e) have shown no dependence on displacement. It leads us to a conclusion predicted analytically in [7, 8, 9, 10] that the variation of motor parameters in a tradition loudspeaker is mostly caused by the presence of iron in traditional loudspeaker.

Replacing the traditional motor by a magnet-only one leads to an increase of the linearity of motor-parts parameters of the Thiele-Small linear model, whatever the displacement of the voice-coil. Thus, contrary to a traditional loudspeaker, the magnet-only loudspeaker can be described more precisely by the simple linear Thiele-Small model with no additional correction to incorporate the nonlinear behavior. This increases the linearity of the loudspeaker, usually correlated with increase of sound quality during the reproduction [21].

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