MEASURING THE NONLINEAR, LOSSY, FREQUENCY-DEPENDENT VOICE COIL INDUCTANCE

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Abstract: The voice coil in electro-dynamic transducers transforms an alternating electrical current into movements that produce sound. An undesirable effect of this principle is the coil's self-inductance, which is highly dependent on the voice coil position and cannot be assumed to be constant. In addition, a single static nonlinear function cannot describe the inductance nonlinearity because eddy currents, the skin effect, and the induced voltage in shorting material such as copper rings cause it to be frequency-dependent. These effects decrease the voltage sensitivity and efficiency of the transducer and create nonlinear distortion that degrades the audio quality. Additionally, DC displacements caused by the reluctance force created by the inhomogeneously distributed magnetic AC flux may decrease the stability of voice coil rest position and maximum excursion. One option for measuring the nonlinear frequency-dependent inductance and magnetic losses involves performing multiple small signal measurements at various voice coil positions. A much faster and novel technique involves performing a single large signal measurement using a multi-tone stimulus to identify parameters for a nonlinear dynamic inductance model. Both methods are discussed in this paper. A meaningful set of easily interpretable results is presented.

1. Introduction

Electro-dynamic moving coil transducers transform an electrical signal into a force using a permanent magnet and a voice coil. A simple ideal inductance cannot model the voice coil's self-inductance as permeable and conductive materials surround it. Instead, it highly depends on the voice coil position and frequency. In addition, the inductance is lossy due to eddy currents or shorting rings. It is crucial to model these effects accurately to simulate and predict a loudspeaker's linear and nonlinear behavior. Accurate modeling and parameter measurement are required for loudspeaker design by transducer and speaker developers and for the active compensation of nonlinear distortion [1]. Several ways to measure the voice coil's self-inductance have been developed and applied. They can be categorized as follows [2]:

- Static and semi-static measurement
- Point-by-point dynamic measurement
- Full dynamic measurement

A static measurement can be performed in multiple ways. One option is to clamp the voice coil and move it to different positions using e.g., a step motor [3]. Due to the fixed voice coil, the mechanical resonator is deactivated. This significantly simplifies the inductance model identification because the electrical impedance $Z(x_{\mathrm{DC}}, f)$only comprises the voice coil's DC resistance and self-inductance. However, measuring without disassembling or modifying parts of the transducer is difficult.

In a point-by-point dynamic measurement, the voice coil is shifted to different positions, and a linear transducer model is identified at each position [2]. One option to shift the voice coil is to mount the device under test in a perfectly sealed enclosure and apply a defined positive or negative static pressure to the back chamber. The disadvantage of this approach is that both the enclosure and the transducer cone and surround must be airtight, which is challenging to accomplish.

Another point-by-point dynamic measurement option is to use a DC voltage to shift the voice coil to different positions.

A full dynamic measurement method has been successfully used in the industry for many years [4]. In this paper, a novel full dynamic measurement method that extends the existing technique is presented. This paper focuses on modeling and interpreting the frequency and displacement dependency of the voice coil's self-inductance. The model shall be easy to interpret and physically interpretable. Flux modulation and hysteresis effects in the iron parts of the transducer's motor are not discussed.

2. Modeling

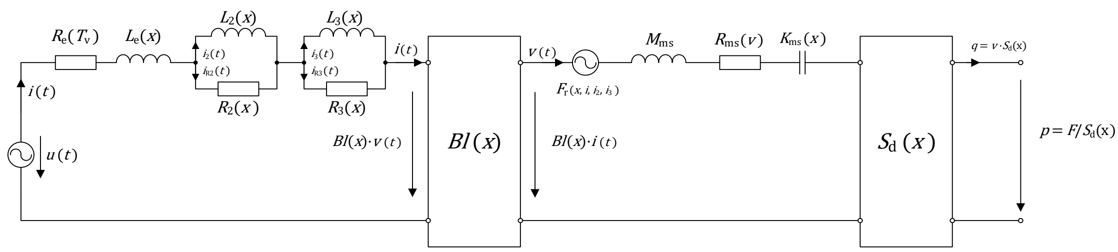

Figure 1: Lumped parameter model of an electro-dynamical loudspeaker.

An electro-dynamic transducer can be modeled with a nonlinear dynamic lumped parameter model, as shown in Figure 1. An excitation voltage $u(t)$ causes an electric current $i(t)$ to flow through the voice coil. The electro-mechanical transduction parameter $Bl(x)$ (*force factor*), which depends on the voice coil displacement x(t) translates this current into a mechanical force $F = Bl(x)i(t)$. This force acts on a resonator that comprises a mass M_{ms}, a nonlinear mechanical stiffness $K_{\text{ms}}(x)$ and a mechanical resistance R_{ms} and moves the voice coil with a velocity $v(t)$. The transducer cone with an effective diameter $S_{\text{d}}(x)$ converts this velocity into a volume velocity and creates a sound pressure $p(t)$. In addition, the voice coil velocity creates a counter-electromotive force (*back-EMF*) that manifests as the voltage $Bl(x)v(t)$. This must be considered in any parameter identification that is based on an electrical measurement.

The coil in a transducer's motor as shown in Figure 2, is not modeled like a simple air coil inductor, which could be modeled with a simple series connection of an ideal inductance L_{e} and an ohmic resistance R_{e} over a wide frequency range. However, the voice coil of an electro-dynamic transducer is more complex. One part of the coil's core is the pole piece, usually made of non-laminated iron with a high permeability. The other part consists of air or a magnet, which both have a relative permeability of $\mu_r = 1$. The ratio between the core materials highly depends on the voice coil position.

The magnetic field induces loops of electric currents in the iron at higher frequencies, illustrated in the Finite Element Analysis in Figure 2. These eddy currents contribute to dissipation and heating. Shorting material can be applied to reduce the inductance. This material is made of a highly conductive material, usually aluminum or copper, and is placed close to the voice coil next to the ring magnet or around the pole piece. This reduces the inductance and its variation over the voice coil position.

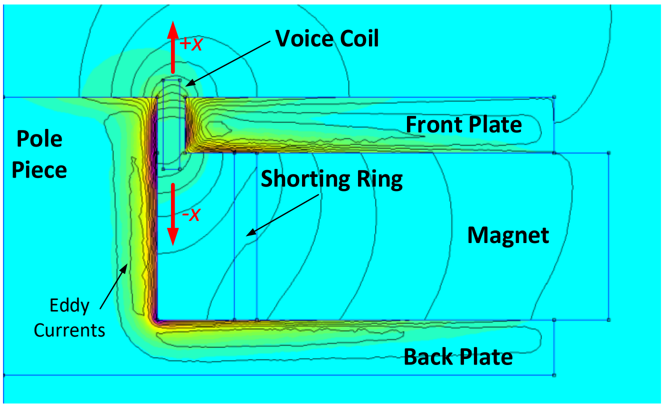

Figure 2: Motor of an electro-dynamic transducer including magnet field lines and the magnetic flux density at 100 Hz.

Different inductance models covering these effects have been developed. Some models use simple electrical elements, such as the single inductance or the LR-2 model [5]. Others are abstract mathematical models, such as the Leach [6] and Wright [7] models, or use fractional derivatives [9]. These models are difficult to interpret and to compare. Vanderkooy [8] introduced a semi-inductance K_s which has an impedance $Z_L(f) = K_S\sqrt{j\omega}$. This has a physical background as it models the skin effect closely related to the eddy currents. Thorborg [10] used the semi-inductance to develop a lumped parameter model that is closely related to the components of the magnetic circuit. While the semi-inductance improves the physical interpretation, it generates complexity in the digital signal processing used in simulation, measurement, and active loudspeaker control.

The LR-*N* model, as shown in Figure 1, was applied in this paper. Its order was limited to $N = 3$. In some cases, an order of 3 is not enough to model the inductance of a transducer over the entire audio bandwidth. In this case, the model can be expanded to an order of $N = 4$ or more.

3. Measurement

3.1. Point-by-point dynamic measurements

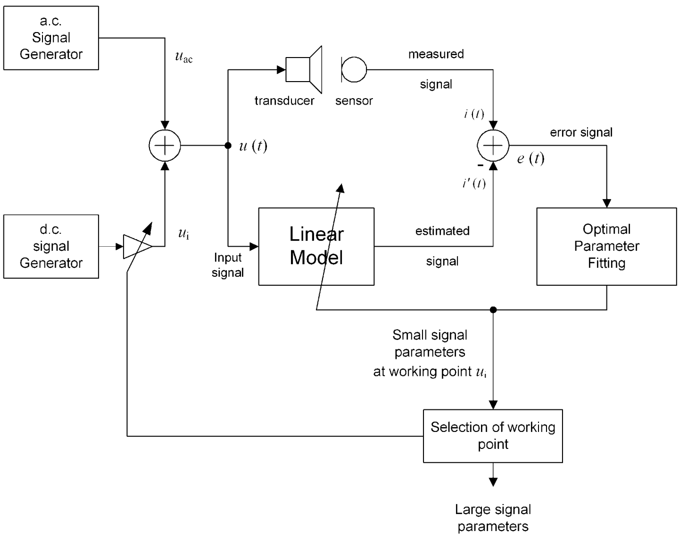

Figure 3: Measurement setup of the point-by-point dynamic measurement [2].

The small signal inductance at the voice coil's rest position $x = 0$ can be measured by applying a small AC voltage and measuring voltage $u(t)$ and current $i(t)$, and calculating the linear transfer function $Z(f) = U(f)/I(f)$. Different stimulus signals with sufficient bandwidth, such as multi-tone, noise, or a sinusoidal chirp, are possible. Based on the measured electrical impedance shown in Figure 4, the elements of the linear electrical lumped parameter model can be identified and separated from each other using an iterative parameter fitting algorithm [9]. The complex impedance comprises the DC resistance R_{e}, the inductance impedance $Z_{\mathrm{L}}(f)$, and the mechano-acoustical resonator that is transformed into the electrical domain $Z_{\mathrm{E,M}}(f)$.

$$Z(f) = \frac{U(f)}{I(f)} = R_{\mathrm{e}}(T_{\mathrm{v}}) + Z_{\mathrm{L}}(f) + Z_{\mathrm{E,M}}(f)$$

The linear inductance impedance $Z_{\mathrm{L}}(f)$ is modeled with the LR-3 model

$$Z_{\mathrm{L}}(f) = j\omega L_{\mathrm{e}} + \sum_{n=2}^{3} j\omega L_n || R_n$$

with the complex frequency $j\omega$. The DC resistance R_{e} which depends on the voice coil temperature T_{v} is measured at a low-frequency tone at $f_{\mathrm{Re}} < 5\ Hz$ where the inductance and the back-EMF $Bl(x)v(t)$ are negligible. The inductance impedance $Z_{\mathrm{L}}(f)$ is the dominant element at higher frequencies.

This linear fitting technique can also be applied to identify a nonlinear inductance model, as shown in Figure 3. This method uses a DC voltage to shift the voice coil to different positions. The DC voltage is superimposed at every position with a small AC signal. The lumped parameter model can then be identified at multiple positions over a large excursion range of the voice coil (Figure 3). For parameter fitting, one must consider that besides the self-inductance, also other model parameters such as the nonlinear force factor $Bl(x)$ and the nonlinear mechanical stiffness $K_{\mathrm{ms}}(x)$ change over the voice coil position. Figure 4 shows the electrical impedances of an example transducer at different voice coil positions.

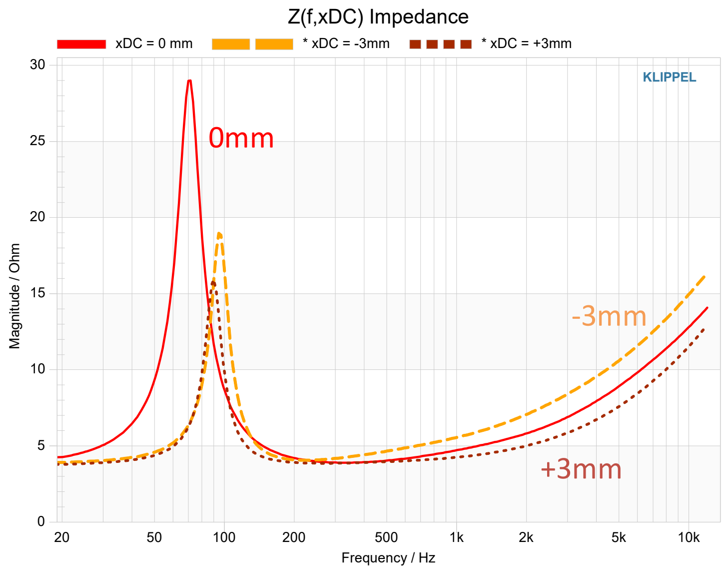

Figure 4: Electrical impedance of an electro-dynamic transducer at different voice coil positions.

In addition to that, some parameters change over time. For instance, the DC resistance R_e increases significantly due to the dissipated power by the DC signal heating the voice coil. Convection cooling is not active because the voice coil velocity is too small. Due to mechanical creep and instantaneous deformation of the suspension geometry, the mechanical stiffness changes over time. Figure 5 shows that the voice coil reaches the final position only after a few seconds. Due to these effects, a pre-excitation of a few seconds is required to ensure that the voice coil position and temperature are sufficiently stable for parameter fitting. A cooling phase should also be included after each measurement where a high DC voltage was applied to avoid significant heating.

These effects can make it challenging to precisely identify the instantaneous DC resistance of the heated coil. There are ways to cope with those issues, but developing a robust, repeatable, universally usable, and easy-to-use measurement procedure is complicated.

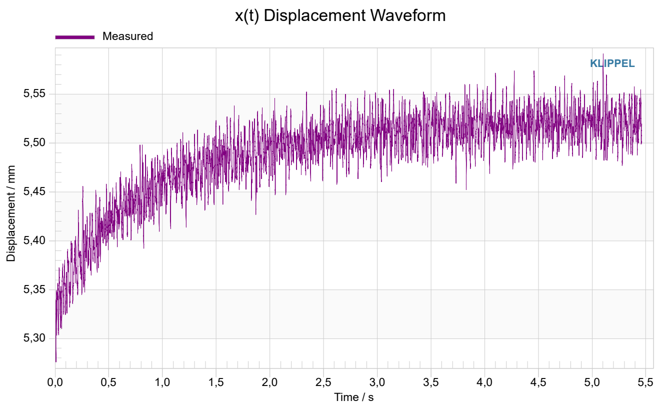

Figure 5: Voice coil displacement over time of a measurement with a DC voltage of 5 V and a multi-tone signal with an RMS voltage of 0.1 V.

3.2. Full dynamic measurement

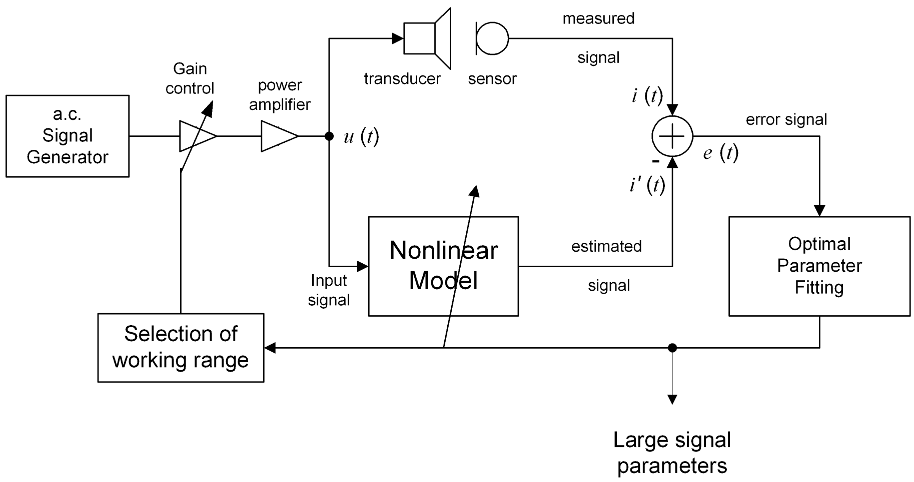

Figure 6: Measurement setup of the full dynamic measurement [2].

Contrary to static or point-by-point measurements, the full dynamic measurement in Figure 6 only requires a single measurement step. This method significantly simplifies the measurement process. The transducer is excited by a multi-tone stimulus. This signal excites many frequencies distributed over a wide frequency range simultaneously. The multi-tone stimulus is used because it provides some significant benefits for a large signal measurement over a random noise signal, which was proposed in [2]:

- the fundamental and the nonlinear distortion can easily be separated, which simplifies parameter fitting
- the multi-tone stimulus spectrum can be shaped to represent typical audio signals (e.g., music)
- the parameter fitting can be evaluated with the residual error
- a low and defined crest factor reduces the amplifier peak requirements
- a deterministic stimulus improves the test repeatability and reproducibility of the results.

The stimulus amplitude must be large enough to move the voice coil over its intended range of operation specified by the user as the maximum voice coil excursion X_{max}. Alternatively, this value can be determined automatically by a protection system that monitors the maximum force factor variation and the mechanical compliance [2], the voice coil temperature, and the impulsive distortion generated by irregular excursion limiting ("rub and buzz"). It must be ensured that the power amplifier can provide sufficient peak voltage and output power. The electrical voltage and current signals are recorded during the measurement, and all linear and nonlinear transducer parameters are identified, as illustrated in Figure 1. A fitting process determines the optimal values for the linear and nonlinear parameters where the error signal $e(t)$, which describes the difference between the measured and modeled currents, becomes a minimum. The residual error reveals the limitations of the modeling. Insufficient modeling of the creep effect, lossy inductance, heating, and loudspeaker nonlinearities can generate a bias in the linear and nonlinear parameters. Hence, the inductance measurement with the full dynamic measurement requires a comprehensive modeling of the loudspeaker in the large signal domain.

Method	**Point-by-Point**	**Full dynamic**
Stimulus	Large DC signal + small AC signal	Large AC signal (e.g. multi-tone)
Representing typical audio signals (music)	No	Yes
Loudspeaker modeling	Linear, thermal and time-varying modeling required	Nonlinear, thermal, and time-varying modeling required
Fitting	Electrical input impedance $Z(f, x_{\mathrm{DC}})$ measured versus DC displacement	Loudspeaker state signals (voltage and current) measured versus time
Nonlinear parameter identification	Exploits variation of linear parameters versus x_{DC}	Exploits nonlinear distortion (intermodulation)
Fitting algorithm complexity	Medium	High
Configuration effort	High	Low
Repeatability	Medium	High
Robustness	Low	High
Accuracy of results	Medium	High
Measurement time	>2 min	<10 sec

Table 1: Comparison of the standard methods used for nonlinear inductance measurement.

Table 1 compares the pros and cons of the two standard methods. The point-by-point method is much simpler and can be realized using conventional equipment for linear parameter measurement, but it is more time consuming and leads to systematic and random errors caused by the DC component in the stimulus. The full dynamic method can identify the free parameters of a more advanced loudspeaker model valid at high amplitudes by exciting the stimulus with any broadband AC stimulus at high amplitudes and monitoring the electrical signals at the terminals in the time domain. Since the full dynamic method provides the parameters with higher accuracy and shorter measurement time, this technique will be considered in the following discussion.

3.3. Results

The full dynamic measurement was performed on two 4" woofers with the properties shown in Table 2. The tested transducers were fixed in a vertical position on a loudspeaker stand. A triangulation laser was used to measure the voice coil excursion. The transducers were not mounted in an enclosure. However, the measurement would also work if the transducers were mounted in a closed or vented enclosure. DUT 1 does not employ any shorting material. DUT 2 has a shorting ring below the gap. Figures 7 and 8 show the identification results of the nonlinear LR-3 model. A negative voice coil displacement corresponds with the voice coil moving into the gap in the direction of the motor's back plate (see Figure 2).

Speaker	**DUT 1** (Visaton W100S)	**DUT 2** (Peerless SDS-P830855)
Rated Diameter	4"	4"
Gap height	4 mm	6 mm
Voice Coil Height	8 mm	12 mm
Voice Coil Diameter	20 mm	25.54 mm
Shorting Material	No	Yes
Magnet Material	Ferrite	Ferrite
Maximum used excursion X_{max}	6 mm	6 mm

Table 2: Properties of two example transducers measured with the full dynamic standard method.

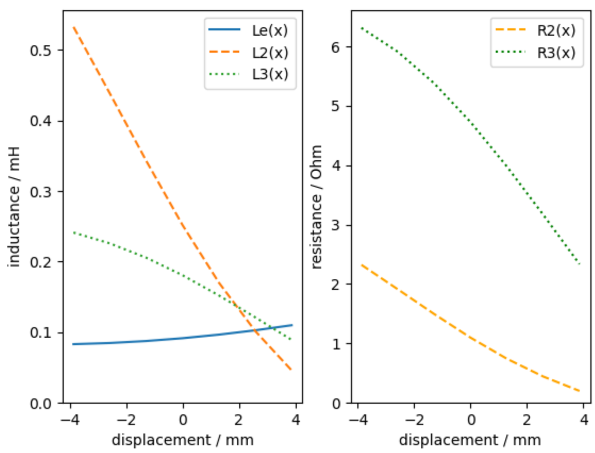

Figure 7: LR-3 parameters DUT 1 measured of the full dynamic method.

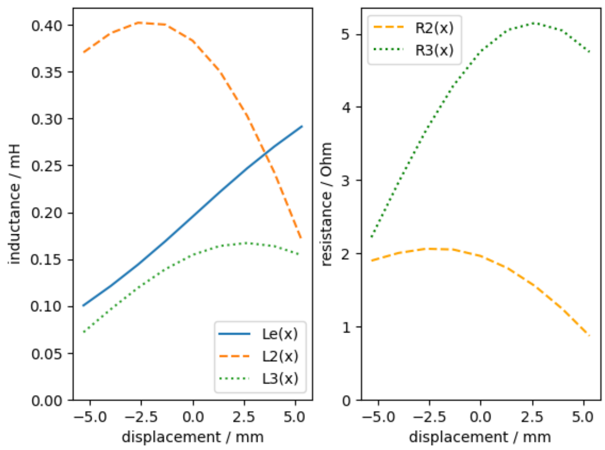

Figure 8: LR-3 parameters of DUT 2 measured with the full dynamic method.

4. Discussion

4.1. LR-*N* model

Modeling the nonlinear and frequency-dependent inductance with an LR-*N* model is robust for parameter identification and for performing simulations in the time domain because of its compact form and relatively small number of free parameters. However, the parameters are not independent. Noise and minor differences in the fitting algorithm can generate significant differences in the LR-*N* parameters, but give a similar total inductance. Thus, the parameters of the LR-3 model shown in Figures 7 and 8 are challenging to interpret. It is unclear which parameters are dominant and in which frequency range they are active. Therefore, evaluating the motor structure and drawing practical conclusions for improving the design (i.e. placing shorting rings) is difficult.

A benefit of the LR-*N* model is that it can be directly applied to calculate the amount of electrical power that is dissipated in the transducer's motor, using

$$P_{\mathrm{iron}} = \sum_{n=2}^{N} i_{\mathrm{R},n}^{2} R_n$$

This model is beneficial for optimizing the efficiency and the thermal behavior. As P_{iron} is dissipated into heat, decreasing it can improve the transducer's long-term power handling. The reactive part of the LR-*N* model can be used to calculate the reluctance force $F_{\mathrm{r}}(x, i, i_n)$ caused by the lossy inductance using

$$F_{\mathrm{r}}(x, i, i_n) = \frac{1}{2}\left(\frac{\mathrm{d}L_{\mathrm{e}}(x)}{\mathrm{d}x} i^2 + \sum_{n=2}^{N} \frac{\mathrm{d}L_n(x)}{\mathrm{d}x} i_n^2\right)$$

This force acts on the voice coil and moves it towards where the magnetic field energy becomes a maximum. The squared current $i_{\mathrm{R},n}$ can generate a DC displacement that can decrease the electro-acoustical efficiency, maximum excursion, and SPL output.

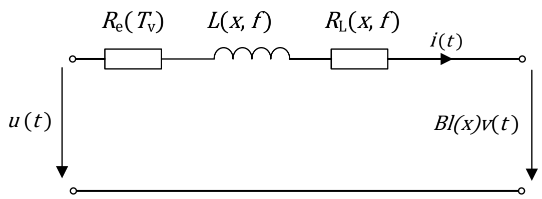

Figure 9: Modeling the nonlinear lossy inductance with separate inductance and resistance elements.

4.2. Parameter Interpretation

To make the physical interpretation of the nonlinear lossy inductance easier and to make it possible to compare different transducers, it is convenient to use inductance and resistance elements as introduced in [3], that depend on the frequency and the voice coil position, as shown in Figure 9. The complex inductance impedance $Z_L(x, f)$, that is calculated with the LR-*N* model is decomposed into the pure inductance and pure resistance parameters

$$L(x, f) = \frac{\Im\{Z_L(x,f)\}}{\omega}$$

and

$$R_L(x, f) = \Re\{Z_L(x, f)\}.$$

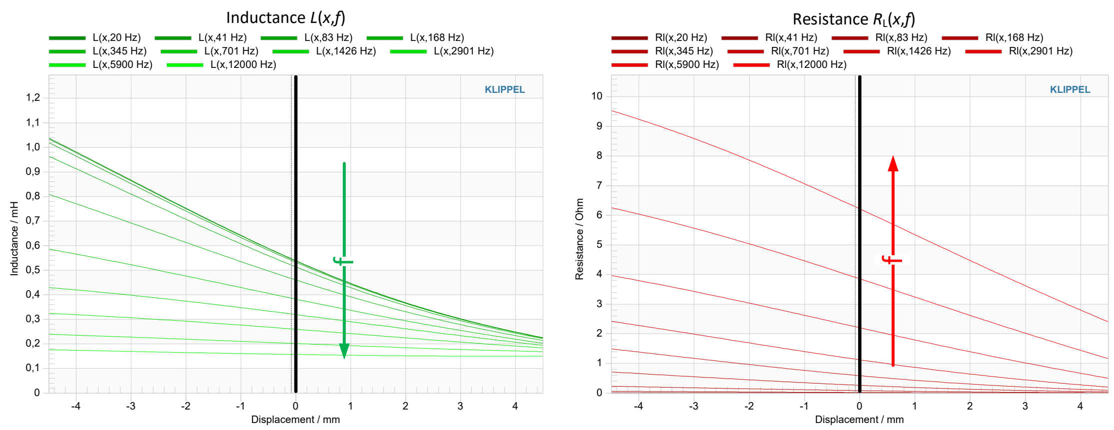

Figure 10: Inductance $L(x, f)$ and resistance $R_L(x, f)$ of DUT 1 (no shorting ring) measured with the full dynamic standard measurement.

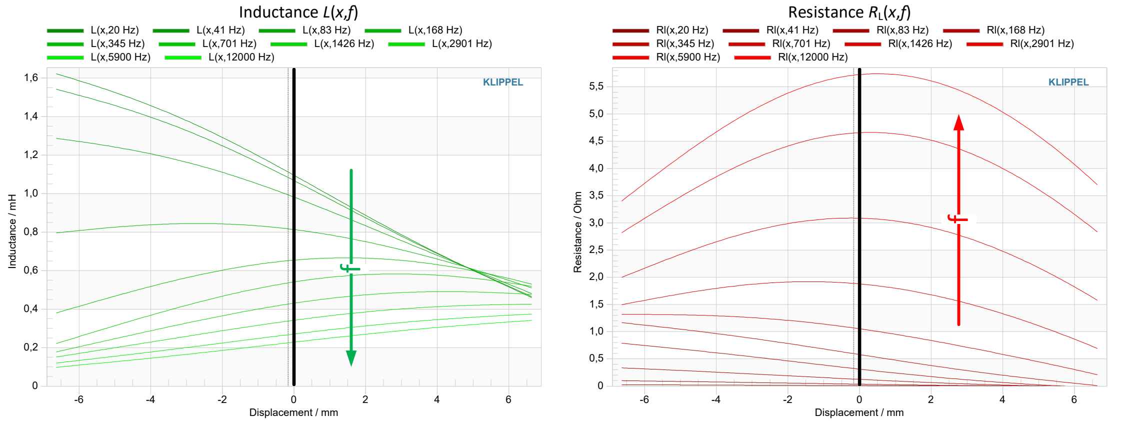

Figure 11: Inductance $L(x, f)$ and resistance $R_L(x, f)$ of DUT 2 (with shorting ring) measured with the full dynamic standard measurement.

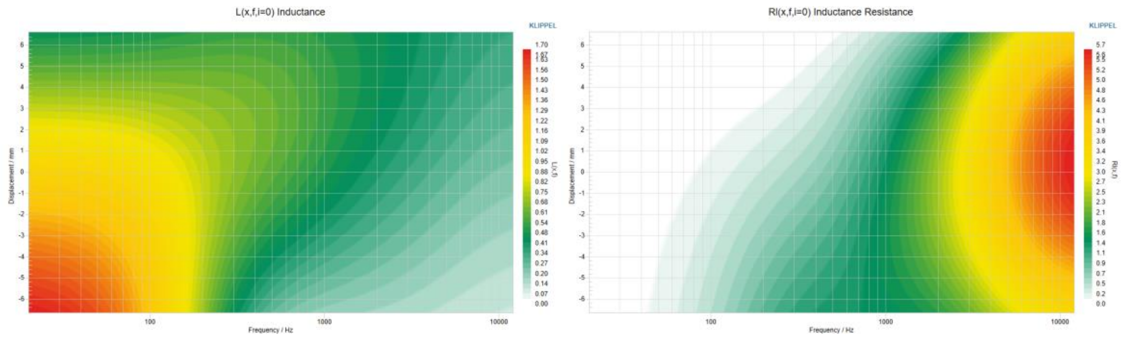

Figure 12: Contour plots of inductance $L(x, f)$ and resistance $R_L(x, f)$ of DUT 2 versus frequency and displacement measured with the full dynamic method.

The effective parameters of the two example transducers, DUT 1 and DUT 2, are shown as a set of curves in Figures 10 and 11. Figure 12 displays the same information for DUT 2 as a contour plot. The inductance $L(x)$ of both transducers exhibits a strong asymmetry at low frequencies. If the voice coil moves inside the gap, the inductance increases because the current i in all coil windings generates a high magnetic flux in the iron path and a high inductance in the coil. If the coil is moved outwards, the inductance drops because only the lower coil windings can contribute to the flux in the iron path.

At low frequencies, the resistance $R_L(x, f)$ is relatively small, indicating that the eddy currents in the iron are negligible. The shorting material mainly impacts higher frequencies, because Faraday's law states that the induced voltage is proportional to the differentiated magnetic flux. Hence, the iron losses $R_L(x)$ are negligible and the inductance impedance is almost purely reactive at low frequencies.

At higher frequencies, the eddy currents generate more dissipation in the iron path and the resistance $R_L(x, f)$ rises with the square root of frequency. As shown in Figure 10, DUT 1 exhibits a $R_L(x, f)$ nonlinearity that changes almost proportionally with the voice coil position. The more iron is in the coil's core, the higher the losses. In addition, the inductance drops because a larger part of the electric input power is not stored as magnetic energy but dissipated into heat.

Contrary to that, both the iron losses and the inductance of DUT 2 decrease when the coil moves towards the back plate at higher frequencies (Figure 11 and 12). The inductance curve even tilts. This is because the magnetic flux created by the voice coil current creates a counter flux in the shorting material which does not contribute to the coil's self-inductance. Hence, the voltage sensitivity increases due to the shorting ring. In addition to that, it decreases the nonlinear distortion because the total inductance and its variation are lower than in a device without shorting material. These benefits come at the cost of an increased bill of materials and a higher effort in production.

4.3. Analysis of Output Distortion

The nonlinear model with the measured parameters allows for calculating a stimulus's sound pressure output for any ordinary audio signal (e.g., music) or artificial test stimuli. The multi-tone stimulus simplifies the distortion analysis because the spectral analysis (Fourier transformation) reveals the fundamental component at the excited frequencies and the total nonlinear distortion at the other frequencies not excited by the stimulus. The total nonlinear distortion contains harmonic and intermodulation distortion generated in all combinations of the fundamental frequencies.

The numerical simulation can also provide the nonlinear distortion generated by each nonlinearity considered in the model, which is useful for evaluating the nonlinearity's impact on the total distortion and to investigate the influence of the stimulus (level, spectrum), the linear transducer parameters (Thiele-Small parameters) and the enclosure type (closed, vented box, passive radiator). Figure 13 shows the fundamental component, total distortion, and the contribution of the dominant transducer nonlinearities for DUT1 and DUT2, respectively.

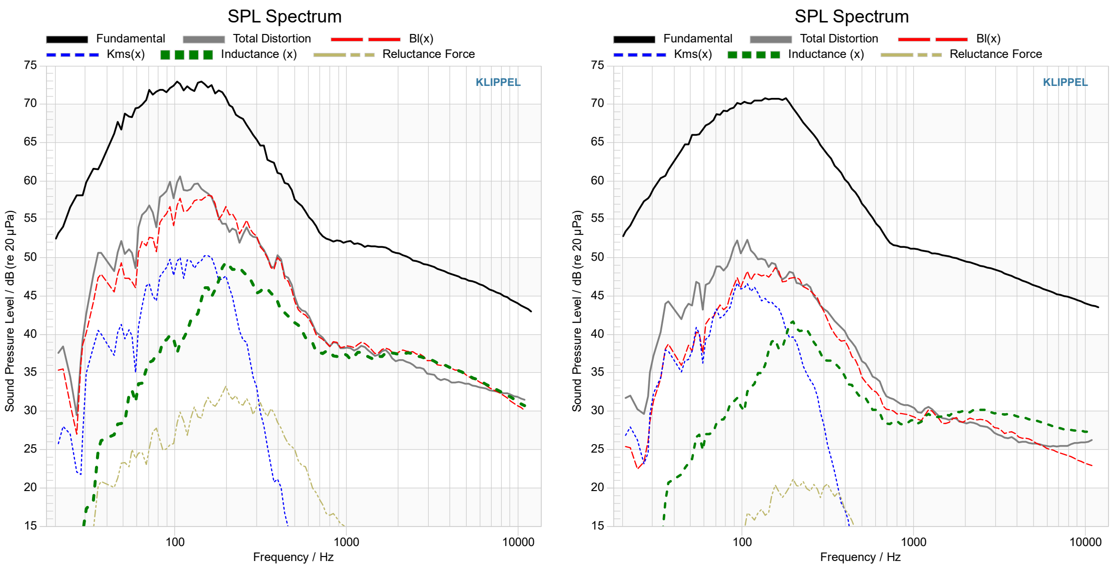

Figure 13: SPL spectrum of the reproduced frequency-shaped multi-tone stimulus simulated with parameters determined by the full-dynamic method of DUT 1 (left) and DUT 2 (right).

The ratio between the SPL of the fundamental and nonlinear distortion is called *multi-tone distortion ratio (MTDR)* according to IEC standards [11] and [12]. DUT 1 in Figure 13 generates a MTDR of about -12 dB throughout in the audio band. DUT 2 generates a much lower MTDR of about -20 dB at a similar peak displacement of $X_{\max} \approx 6$ mm. In both transducers, the nonlinear force factor $Bl(x)$, followed by the nonlinear mechanical stiffness $K_{\mathrm{ms}}(x)$, are dominant at low frequencies. However, DUT 2 uses a larger voice coil height and more coil overhang as listed in Table 2, providing less force factor $Bl(x)$ variation. The nonlinear inductance contributes significant intermodulation distortion at higher frequencies $f > 200$ Hz caused by the high voice coil excursion generated by a low frequency component (bass signal). An interesting effect occurs when comparing the contributions of $Bl(x)$ and the inductance $L(x)$

with the total distortion, which is lower in amplitude. This is caused by a partial cancellation of the two effects at high frequencies at $f > 2$ kHz. The shorting ring used in DUT 2 is very beneficial and reduces the inductance nonlinearity $L(f, x)$ generated by the longer coil.

The nonlinear distortion caused by the reluctance force is negligible in both transducers. However, if the transducers are operated in a small closed box, a higher electrical current is required to move the voice coil to its full range. Then, the reluctance force can become critical due to the generated DC force which reduces the voice coil stability. A DC displacement generated dynamically by the transducer nonlinearities can significantly degrade the audio quality due to the added harmonic and intermodulation distortion.

5. Conclusion

A novel dynamic measurement technique is presented to measure the lossy inductance nonlinearity of any electro-dynamic transducer such as woofers, tweeters, headphones or micro-speakers. It provides more robustness, accuracy, and speed than a conventional point-by-point measurement.

The LR-*N* model is a useful abstraction of the electromagnetic dynamics in transducers using a minimum of free parameters. It is well suited for loudspeaker simulations and for estimating the nonlinear distortion created by the nonlinear inductance. The model also provides a basis for loudspeaker control, such as active cancelation of nonlinear distortion, because it can be implemented by using IIR filters and power series expansions, which generate low processing costs and memory requirements for digital signal processors. Furthermore, it makes the reluctance force and iron loss calculations simple. Unfortunately, its parameters are difficult to interpret and are less useful for loudspeaker design.

The paper showed that the nonlinear lossy inductance can be represented by the pure inductance and resistance elements $L(x, f)$ and $R_{\mathrm{L}}(x, f)$ which simplifies physical interpretation of the measurement results, evaluation of design choices, and distortion analysis.

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Wolfgang Klippel studied electrical engineering at the University of Technology in Dresden, in the former East Germany, where his initial studies focused on speech recognition. Afterward, he joined a loudspeaker company in eastern Germany, where he was engaged in transducer modeling, acoustic measurement, and psychoacoustics. He returned to his studies and received a Ph.D in Technical Acoustics in 1987. After a post-doctoral year at the Audio Research Group in Waterloo, Canada, and working at Harman/JBL in Northridge, CA, he returned to Dresden in 1997 and founded Klippel GmbH. This company develops novel control and measurement systems for loudspeakers and other transducers. Dr. Klippel has also been engaged as Professor of Electro-acoustics at the University of Technology in Dresden since 2007. His papers and tutorials on loudspeaker modeling and measurement – particularly those on large-signal behavior and physical distortion mechanisms –are considered reference works in the field.