Nonlinear Parameters Identification of Moving Coil Miniature Loudspeakers

Diego Hernandez and Yu Mong Yu
Merry Electronics
Taichung, Taiwan
e-mail: diego.hernandez@merry.com.tw,
gere.yu@merry.com.tw

Jin Huang
Department of Mechanical and Computer-Aided Engineering
Feng Chia University
Taichung, Taiwan
e-mail: jhhuang@fcu.edu.tw

***Abstract*—Due to its physical design, moving coil loudspeakers exhibit distortion at high excursion signals. The identification of the nonlinear parameters gives the physical cause of the distortion, which is important for diagnostics and allows for a more realistic modeling. This work presents a measurement system for nonlinear parameters of miniature moving coil loudspeakers by using voltage, current and laser displacement sensors. The voice coil electrical resistance (R_E) and the mechanical mass (M_{MS}) are defined as linear parameters. As nonlinear parameters, the force factor (Bl), the stiffness (K_{MS}) and the voice coil inductance (L_E) are defined as a function of the instantaneous voice coil displacement. In addition, for microspeakers characterization, the mechanical resistance (R_{MS}) is defined as a function of the voice coil velocity. In order to identify the parameters, the driver under test is excited by a large amplitude signal meanwhile the voltage, the current and the voice coil displacement are acquired. The measured signals are then fitted in time domain by using nonlinear least-squares identification technique to the ones numerically obtained from the modeled loudspeaker. Measurement results demonstrate the reliability of the measurement system.**

Keywords-miniature loudspeaker; system identification; measurement system; laser displacement sensor

I. INTRODUCTION

Loudspeakers and microspeakers have become a common part of daily life, being integrated in phones, computers, TVs, cars or PA systems. Among different loudspeaker types, the ones using the electro-dynamical principle are commonly preferred for most of the applications due to their simple mechanism, performance and low cost.

The modeling of loudspeakers represents a powerful tool for designing and provides the prediction of the transducer performance. A common method to describe the driver is by a lumped-parameter model, which uses the set of Thiele-Small (small signal) parameters to define its behavior [1]. Traditional techniques analyze the impedance function to obtain the parameters that represent the electrical part of the model. However, in order to obtain the parameters that represent the mechanical part, a second measurement has to be performed by altering the loudspeaker mechanical mass or adding an enclosure. This method is time consuming and not reliable. By using a triangulation laser sensor, the displacement of the voice coil can be simultaneously acquired with the current and the voltage. The electrical and the mechanical parameters can be then accurately obtained with a single measurement [2]-[5].

Linear models can describe the loudspeaker operating under low excitation signals. However, when a loudspeaker is driven by a large signal, it exhibits distortion and the linear model fails to accurately simulate its behavior. Therefore, to improve the modeling, the driver becomes defined by including nonlinear parameters [6]-[7]. In order to obtain these nonlinear parameters several identification methods have been proposed [8]-[12].

The measurement of the distortion only provides information about the nonlinear symptoms of the driver. However, the identification of the nonlinear parameters gives the physical cause of the distortion. Accurate identification of loudspeaker parameters, without the need of complex operational processes or expensive equipment, still represents an important part of the research applied to loudspeakers. This work presents a practical measurement system for the identification of electro-dynamic loudspeakers parameters. This system performs in accordance to the full-dynamic method described in the IEC 62458 standard [13]. The driver under test is stimulated by a large amplitude signal while the voltage, the current and the voice coil displacement are acquired. These signals are then fitted in time domain by using nonlinear least-squares identification technique to the ones numerically obtained from the modeled loudspeaker. The voice coil electrical resistance and the mechanical mass (M_{MS}) are defined as linear parameters. As nonlinear parameters, the force factors (Bl), the stiffness (K_{MS}), the voice coil inductance (L_E) are defined as a function of the instantaneous voice coil displacement. In order to accurately characterize small-sized drivers, the mechanical resistance (R_{MS}) is defined as a function of the velocity of the voice coil [6]. The signal processing and identification process is controlled and monitored by a computer via Graphical User Interface.

II. LOUDSPEAKER MODEL

The loudspeaker is an electromagnetic transducer that produces sound from an electrical signal coupling electrical, mechanical and acoustical domains. A typical moving coil transducer is composed of a magnetic system (magnet and

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polar piece) and mechanical system (diaphragm and voice coil).

When an electrical signal is applied to the voice coil, the current generates a magnetic field that interacts with the flux of the magnet, generating mechanical force. The acoustic radiation is produced by the diaphragm that moves while it is attached to the voice coil. Elastic suspensions keep the diaphragm and the voice coil in the correct working position, allowing for the movement in an axial direction.

The behavior of the moving coil transducer can be expressed as

$$u(t) = R_E i(t) + L_E \frac{di(t)}{dt} + Bl \frac{dx(t)}{dt} \quad (1)$$

$$Bli(t) = M_{MS} \frac{d^2x(t)}{dt^2} + R_{MS} \frac{dx(t)}{dt} + K_{MS} x(t) \quad (2)$$

In the electrical domain, *u(t)* is the input voltage and *i(t)* is the voice coil current. The electrical parameters are L_e and R_e. In the mechanical domain, *x(t)* is the displacement of the voice coil. The mechanical parameters are K_{MS}, *Bl*, M_{MS} and R_{MS}.

The principal causes of nonlinearity in loudspeakers at low frequencies depend on the voice coil excursion *x*. The dominant nonlinearities are the inductance, the force factor and the stiffness. In addition, for small-sized drivers with high resonance frequency and small force factor, the mechanical resistance depending on the voice coil velocity also becomes a significant nonlinearity [6]. The nonlinear parameters are then defined as

$$K_{MS}(x) = \sum_{i=0}^{N} K_{MSi} x^i \quad (3)$$

$$Bl(x) = \sum_{i=0}^{N} Bl_i x^i \quad (4)$$

$$L_E(x) = \sum_{i=0}^{N} L_{Ei} x^i \quad (5)$$

$$R_{MS}(v) = \sum_{i=0}^{N} R_{MSi} v^i \quad (6)$$

By using these power series expansions, a reasonable accurate fitting to the nonlinear parameters is obtained by using five coefficients. The parameters are then represented over the measured displacement and velocity ranges.

III. MEASUREMENT SYSTEM

The IEC 62458 standard defines several methods to obtain the nonlinear parameters of loudspeakers: static method, point-by-point dynamic method and full-dynamic method. This work covers the full-dynamic method, which is the only method that operates the driver under real working conditions.

A. Excitation and Acquisition

As shown in Fig. 1, to perform the measurement the driver is fixed on a stand in vertical position. The loudspeaker is connected to the power amplifier, which drives the stimulus signal. Meanwhile the driver is being excited; the voltage, the current, and the displacement signals are acquired by the sensors. The voltage signal is directly measured over the driver terminals. The current signal is obtained by measuring the voltage over a resistor placed in series with the driver. The displacement signal is measured by a laser displacement sensor that perpendicularly points to the diaphragm. These signals are simultaneously acquired by the DAQ system, and then stored in the computer to perform the identification of the parameters. Fig. 2 shows the experimental process of the measurement system.

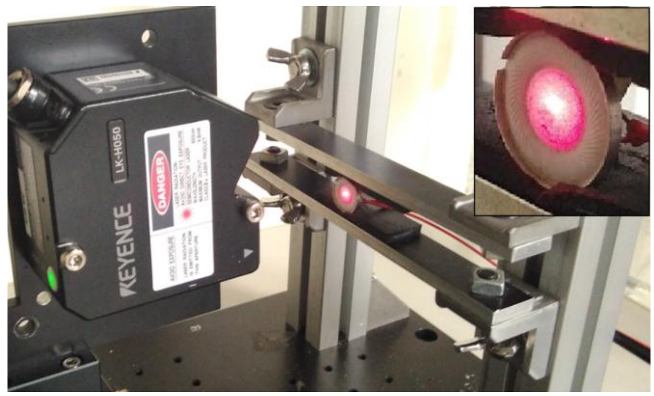

Figure 1. A moving coil microspeaker placed on the stand of the measurement system.

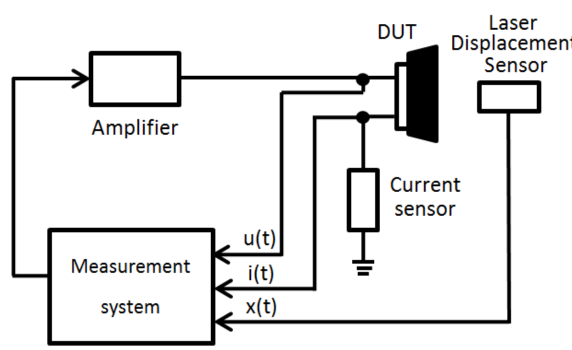

Figure 2. Experimental measurement process.

The accuracy in the signal acquisition is crucial in order to obtain reliable measurement results. Floating input is used to measure the voltage over the speaker terminals and avoid the influence of the cable resistance. In addition, the delay of the laser displacement sensor has to be accurately compensated before the identification process.

B. Identification of Parameters

During the measurement process, the driver exhibits all of the nonlinearities. Therefore, the identification has to simultaneously involve all of the parameters. The measurement begins with the excitation of the driver with a pink noise stimulus, which concentrates the spectral density in low frequency. Once the voltage, current and displacement signals are acquired, the nonlinear parameters are obtained by fitting (1) and (2) to the measured time domain signals. In the identification process, the Gauss Newtown algorithm is used to solve the nonlinear least squares optimization. This algorithm iteratively finds the minimum of the sum of squares, beginning from the initial guesses.

In order to let the driver move at high excursion, the measurement is then iteratively performed at different stimulus amplitudes starting from an initial low amplitude. The measurement process increases the output voltage at each iteration until a limit is reached. This limit is decided by the user, avoiding the driver to be damaged. The limit is set as a combination of voltage, current, power and displacement. For each iteration, during the identification process, the loudspeaker remains without excitation in order to prevent the temperature of the voice coil from rising.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

This section discusses the measurement results of the 1 cm diameter microspeaker shown in Fig. 1. The set of linear parameters are first obtained by a 0.1 V_{RMS} stimulus, which assures enough signal-to-noise ratio with a negligible distortion. If the excursion of the driver is low, the nonlinear coefficients can be omitted and the rest of parameters can be considered linear. These small signal parameters are then used as the initial guesses for the nonlinear identification process.

The nonlinear parameters are obtained by exciting the driver with a 1.5 V_{RMS} stimulus, which reproduces a maximum voice coil excursion of 0.43 mm outside direction and 0.37 mm inside direction. Fig 3, 4 and 5 show a subset of the acquired signals for the voltage, the current, and the displacement, respectively. Fig. 4 demonstrates the good agreement for the measured and the estimated current signals; as well as Fig. 5 shows the same result for the measured and the estimated displacement signals.

The identified parameters for small and large signal cases are summarized in Table I. It can be observed that the parameters vary as the amplitude is increased. This effect is more notorious in K_{MS}, indicating that the suspension becomes softer at large amplitudes.

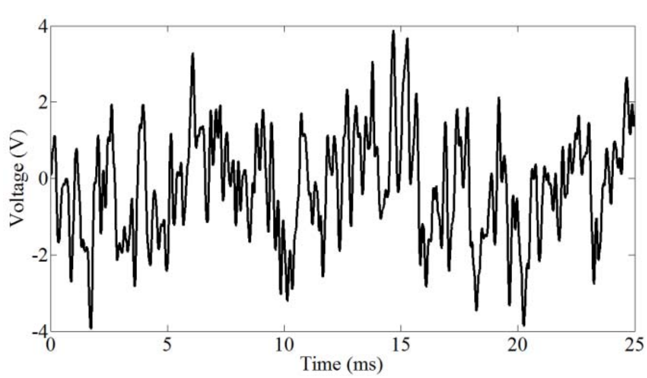

Figure 3. Measured voltage signal at speaker terminals.

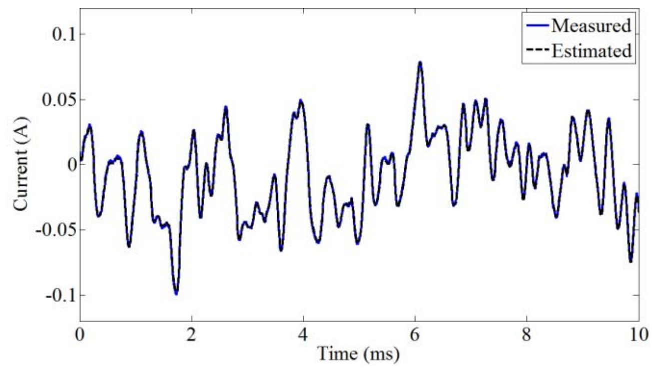

Figure 4. Measured and estimated voice coil current.

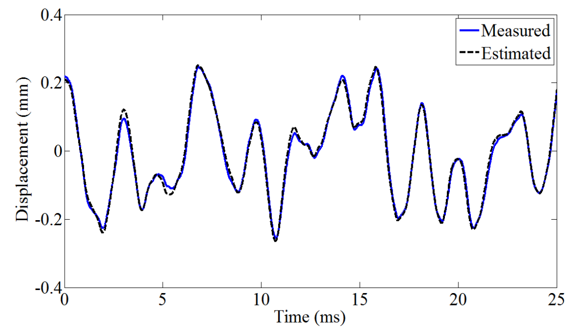

Figure 5. Measured and estimated voice coil displacement.

TABLE I. LINEAR AND NONLINEAR PARAMETERS

Parameter	***Linear Small Signal***	***Nonlinear Large Signal***	***Units***
R_E	39.4	39.4	Ohm
M_{MS}	0.021	0.020	g
Bl_0	0.51	0.49	N/A
Bl_1	-	-0.02	N/Amm
Bl_2	-	-0.43	N/Amm^2
Bl_3	-	0.10	N/Amm^3
Bl_4	-	-0.10	N/Amm^4
L_{E0}	0.039	0.042	mH
L_{E1}	-	-0.030	mH/mm
L_{E2}	-	0.010	mH/mm^2
L_{E3}	-	-0.004	mH/mm^3
L_{E4}	-	0.004	mH/mm^4
K_{MS0}	0.121	0.093	N/mm
K_{MS1}	-	-0.084	N/mm^2
K_{MS2}	-	0.367	N/mm^3
K_{MS3}	-	0.020	N/mm^4
K_{MS4}	-	0.020	N/mm^5
R_{MS0}	0.012	0.013	kg/s
R_{MS1}	-	-0.009	kg/smm
R_{MS2}	-	0.035	kg/smm^2
R_{MS3}	-	0.000	kg/smm^3
R_{MS4}	-	0.000	kg/smm^4

Once the nonlinear coefficients are identified, (3)-(6) are used to graph the nonlinearities over the measured displacement and velocity ranges. Fig. 6, 7, 8 and 9 show the curves of K_{MS}, Bl, L_E and R_{MS}, respectively. It can be observed that K_{MS} exhibits a strong nonlinear behavior with an offset of 0.1 mm in the resting position of the voice coil. This causes that the stiffness is increased 45% at the maximum measured excursion. In Fig. 8 it can be noted a reduction of 10% on the force factor at the maximum excursion, which also reveals its nonlinear behavior. In Fig. 10, the nonlinear mechanical resistance reveals a significant effect of the air loading, which causes an increment on the mechanical resistance.

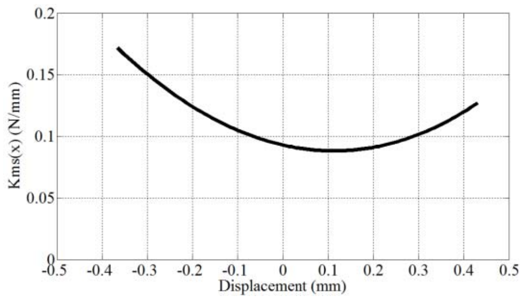

Figure 6. Stiffness (K_{MS}) versus displacement.

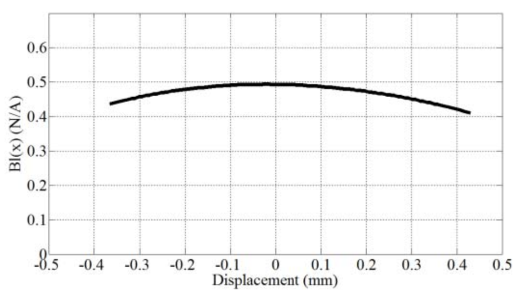

Figure 7. Force factor (Bl) versus displacement.

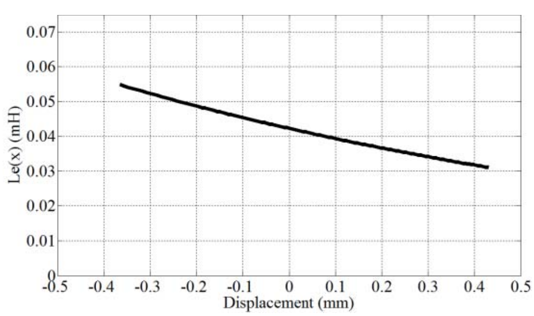

Figure 8. Voice coil inductance (L_E) versus displacement.

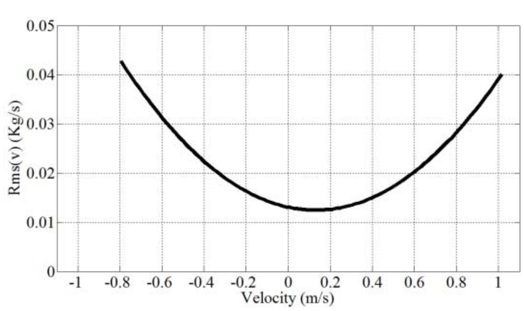

Figure 9. Mechanical resistance (R_{MS}) versus velocity.

In order to verify the model and the identification, the measured nonlinear symptoms of the driver are compared with the predicted ones. The most representative symptom is the compression of the voice coil displacement [14]. Fig. 10 shows the good agreement between the measured and predicted displacement. In addition, it is shown that neglecting the nonlinearities would produce a significant peak and bottom displacement increment around the resonance frequency.

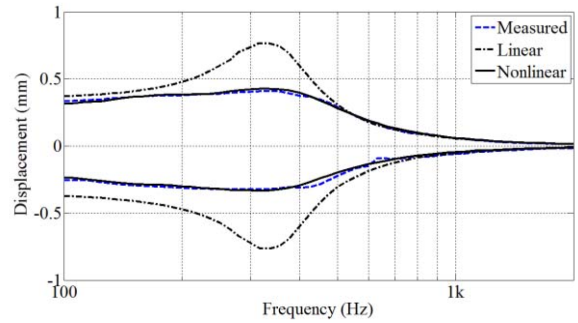

Figure 10. Measured and estimated voice coil displacement.

A common method to obtain the nonlinearities symptoms of loudspeakers is by measuring the Total Harmonic Distortion (THD). Fig. 11 shows the matching of the measured THD in the displacement signal with the predicted one. It can be observed that the distortion increases bellow the resonance frequency.

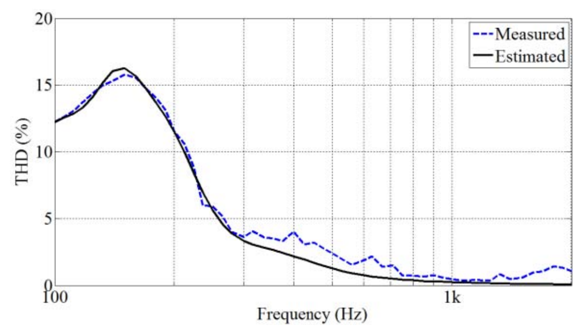

Figure 11. Measured and estimated THD of the voice coil displacement.

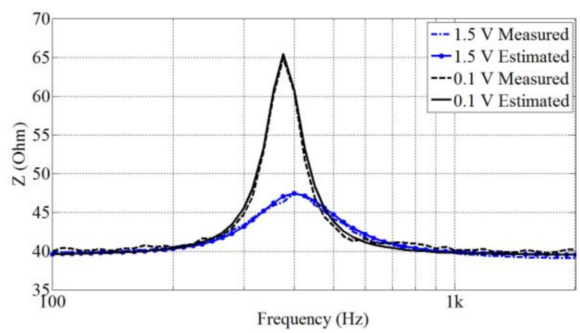

Figure 12. Measured and estimated electrical impedance for small signal ($0.1\ V_{RMS}$) and large signal ($1.5\ V_{RMS}$) excitations.

The electrical parameters R_E and L_E define the electrical impedance ($Z=U/I$). Fig. 12 shows the impedance functions for small (0.1 V_{RMS}) and large signal (1.5 V_{RMS}) excitations. Good agreement is obtained between the curves by exciting the real driver and the modeled one with similar stimulus. It can be observed that the maximum impedance is reduced and the resonance frequency is increased when the driver is excited by the large signal.

The voltage to displacement transfer function ($H=X/U$) is defined by the mechanical parameters K_{MS}, Bl, R_{MS} and M_{MS}. Fig. 13 shows the transfer functions H for small and large signal excitations, where the estimated transfer functions have a good agreement with the measured ones. It can be observed a significant compression around the resonance frequency by increasing the amplitude of the stimulus from 0.1 to 1.5 V_{RMS}.

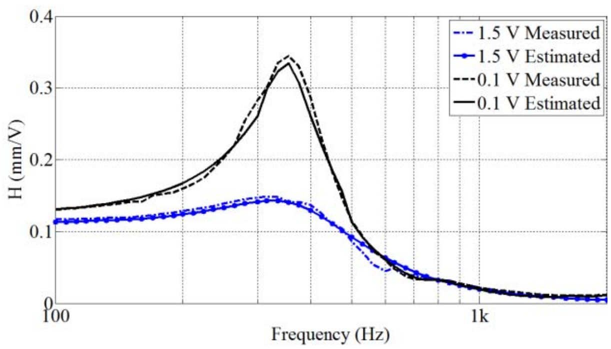

Figure 13. Measured and estimated voltage to displacement transfer functions for small signal (0.1 V_{RMS}) and large signal (1.5 V_{RMS}) excitations.

V. CONCLUSIONS AND FUTURE WORK

This work presented an efficient, fast and accurate measurement system for miniature dynamic loudspeakers. This system offers reliability for nonlinear parameter identification without there being a need for expensive equipment and complex operational processes. The system is appropriate for the measurement of small-size loudspeakers due to the representation of R_{MS} as a nonlinear parameter.

The performance of the measurement system was confirmed by experimental validations. The current and displacement time domain signals were shown with very low fitting errors. For verification purposes, measured voice coil excursion, THD, electrical impedance and displacement transfer function are compared with the ones numerically obtained from the identified model.

The microspeaker nonlinearities can be modeled with reasonable accuracy by defining Bl, K_{MS}, L_E as a function of the voice coil displacement, and R_{MS} as a function of the voice coil velocity. For more accurate modeling, it may be considered other phenomena, such as the thermal effects. Additionally, the dependency of the Bl and L_E on the voice coil electrical current also affects large size loudspeakers. The inclusion in the identification system of both, thermal effect and current dependency, remain to be included in future work.

REFERENCES

[1] L. L. Beranek, Acoustics. American Institute of Physics, 1986.

[2] U. Seidel and W. Klippel, “Fast and Accurate Measurement of the Linear Transducer Parameters,” presented at the Audio Engineering Society Convention 110, 2001.

[3] Y.-T. Tsai, C.-C. Wang, and J. H. Huang, “An inverse method for estimating the electromechanical parameters of moving-coil loudspeakers,” J. Acoust. Soc. Am., vol. 134, no. 5, pp. 3594–3604, Nov. 2013.

[4] M. H. Knudsen, J. G. Jensen, V. Julskjaer, and P. Rubak, “Determination of loudspeaker driver parameters using a system identification technique,” J. Audio Eng. Soc., vol. 37, no. 9, pp. 700–708, 1989.

[5] J. N. Moreno, “Measurement of Loudspeaker Parameters Using a Laser Velocity Transducer and Two-Channel FFT Analysis,” J. Audio Eng. Soc., vol. 39, no. 4, pp. 243–249, Apr. 1991.

[6] W. Klippel, “Modeling the Large Signal Behavior of Micro-Speakers,” presented at the Audio Engineering Society Convention 133, 2012.

[7] E. S. Olsen and K. B. Christensen, “Nonlinear Modeling of Low-Frequency Loudspeakers-A More Complete Model,” presented at the Audio Engineering Society Convention 100, 1996.

[8] W. Klippel, “Measurement of Large-Signal Parameters of Electrodynamic Transducer,” presented at the Audio Engineering Society Convention 107, 1999.

[9] G. Cibelli, A. Bellini, and E. Ugolotti, “Dynamic measurements of low-frequency loudspeakers modeled by Volterra series,” in Audio Engineering Society Convention 106, 1999.

[10] W. Klippel, “Dynamic Measurement and Interpretation of the Nonlinear Parameters of Electrodynamic Loudspeakers,” J. Audio Eng. Soc., vol. 38, no. 12, pp. 944–955, Dec. 1990.

[11] H. Jeong and J.-G. Ih, “Harmonic Balance Method for Estimating the Nonlinear Parameter of Electrodynamic,” J. Audio Eng. Soc., vol. 44, no. 4, pp. 245–257, Apr. 1996.

[12] R. J. Mihelich, “Loudspeaker Nonlinear Parameter Estimation: An Optimization Method,” presented at the Audio Engineering Society Convention 111, 2001.

[13] IEC Standard 62458: Sound system equipment - Electroacoustical transducers - Measurement of large signal parameters. International Electrotechnical Commission, Geneva, Switzerland.

[14] W. Klippel, “Assessment of Voice-Coil Peak Displacement Xmax,” J. Audio Eng. Soc., vol. 51, no. 5, pp. 307–324, May 2003.