Electroacoustic analysis of an electret loudspeaker using combined finite-element and lumped-parameter models

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An unconventional type of electrostatic loudspeaker is presented in this paper. The loudspeaker made of thin, light, and flexible electret material lends itself well to the space-concerned applications. Electrical impedance measurement reveals that the coupling between the electrical system and the mechanical system is weak, which renders conventional parameter identification based on electrical impedance measurement impractical. A different approach is thus employed to model the electret loudspeaker. To predict the loudspeaker's dynamic response, finite-element analysis (FEA) is conducted on the basis of a simple model and a full model. In the simple model, FEA is applied to model the electret membrane, leaving the rest of system as rigid parts. In the full model, FEA is applied to model the entire membrane-spacer-back plate assembly. Velocity response of the membrane subject to a uniformly distributed force is calculated using FEA harmonic analysis. Mechanical impedance is then calculated with the velocity response. The acoustical impedance due to the back cavity, pores, and the radiation loading at the front side is calculated by theoretical formulas. The volume velocity of the membrane and the resulting on-axis sound pressure level are predicted with electrical-mechanical-acoustical analogous circuits. The response data predicted by the simulation compare very well with experimental measurements.

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I. INTRODUCTION

A flat type of loudspeaker based on electret technology is presented in this paper. The loudspeaker is made of thin, light, and flexible electret material, which lends itself very well to space-concerned applications as demanded by many 3C (computer, communication, and consumer electronics) products. This paper aims to model the electret loudspeaker and assess the acoustical performance using a combined finite-element and lumped-parameter model. Being able to simulate the response of the transducer is crucial to optimizing the performance of this special type of transducer.

The principle of the electret loudspeaker resembles that of electrostatic loudspeakers. An electrostatic loudspeaker exploits the varying electrostatic force generated between two charged plates separated by an air gap. In the 1930s, there were a number of practical electrostatic loudspeakers invented.[1] McLachlan[2] conducted theoretical investigations of sound power and pressure at resonant and non-resonant frequencies on a stretched-membrane electrostatic loudspeaker. On the other hand, electret is a dielectric material that has a quasi-permanent electric charge or dipole polarization. An electret generates internal and external electric fields, and is the electrostatic equivalent of a permanent magnet. There is a similarity between electrets and the dielectric layer used in capacitors; the difference being that dielectrics in capacitors possess an induced polarization that is only transient, dependent on the potential applied on the dielectric, while dielectrics with electret properties exhibit quasi-permanent charge storage or dipole polarization in addition. Paajanen *et al.*[3] modeled the electret film using a simplified model involving multiple parallel air gaps. Reciprocity of the sensor and actuator is demonstrated experimentally using the model. Mellow and Karkkainen[4] calculated the free-space radiation of a tensioned circular membrane. Near-field and far-field pressure responses and efficiency were calculated based on the diaphragm impedance. The on-axis pressure response calculated using this method was compared with that obtained using a finite-element model. Medley *et al.*[5] analyzed an electrostatic transducer analytically and numerically. The frequency response of the transducer with layered construction was calculated and compared with experimental data.

Electret transducers have advantage over conventional electrostatic transducers to enable simple and compact electroacoustic construction without external polarization circuit and power supply. A celebrated example is the electret condenser microphone invented at Bell laboratories in 1962 by Sessler and West,[6] using a thin metalized Teflon foil. Rather than the well established microphone technology, the reciprocal application of electret material to loudspeakers is attempted in this paper. Over the past years, various polymer materials such as polyethylene, polystyrene, polyurethane, polyethyleneterephtalate, Teflon (FEP and PTFE), polyvinylidene fluoride, and polypropylene (PP) have been used as electret materials.[7,8] These are usually homogeneous solid materials. Paajanen *et al.*[8] suggested a new multipurpose material, electromechanical film (EMFi). The EMFi is a thin, cellular, biaxially oriented PP film that can be used as an

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electret. Having a special voided internal structure and high resistivity, it is capable of storing large permanent charge. EMFi can be applied to sensors, switches, loudspeakers, special transducers, etc. Saarimaki *et al.*[9] developed heat-resistive sensors and actuators using electromechanical cyclo-olefin-based polymer films. They described in detail the manufacturing of electromechanical and electrostatic transducers used in the audible frequency range. Recently, Chiang and Chen[10] proposed a new flexible electret loudspeaker using nano-technology. The electret diaphragms are fabricated using fluoro-polymer with nano-meso-micro pores precharged by the corona method. Heydt *et al.*[11] measured the acoustical response produced by electrostrictive polymer film loudspeakers. Measurements of harmonic distortion are also shown, accompanied with results demonstrating reduced harmonic distortion achieved using a square-root wave shaping technique.

This paper aims at establishing a simulation platform for electret loudspeakers with the main structure consisting of a membrane, a spacer grid, and a back plate. Due to the effect of the spacer grid, the membrane is rigidly constrained at the grid such that the motional impedance presented in the terminal electrical impedance is almost negligible. As we shall see later in the presentation, the characteristics of the mechanical system are not present in the electrical domain and the effective electrical impedance resembles that of a capacitor. Electrical impedance measurement reveals that the coupling between the electrical system and the mechanical system is weak, which renders conventional parameter identification based on electrical impedance measurement[12–14] impractical in the case of electret loudspeakers. In this paper, a different approach is thus employed to model the electret loudspeaker by taking advantage of the fact that the electrical and the mechanical systems are weakly coupled. Specifically, the electrical response is treated as a capacitor without considering the mechanical loading, whereas the mechanical response is calculated by using the unloaded electrical response as the input to the mechanical systems. Finite-element analysis (FEA) is employed in a simple model as well as a full model to predict the loudspeaker's dynamic response. The FEA model is tuned by matching the resonance frequency predicted by a single-cell model with the velocity response measured by a laser vibrometer. The mechanical impedance is estimated by the average velocity response subjected to a uniformly distributed force. Furthermore, the acoustical impedance due to the back cavity, pores, and the radiation loading at the front side is calculated by the theoretical formulas. Using this hybrid model, the volume velocity of the membrane and the on-axis sound pressure level (SPL) can be calculated with accuracy.

II. OPERATING PRINCIPLES OF AN ELECTRET LOUDSPEAKER

A sample of electret loudspeaker with length 101 mm and width 41 mm is shown in Figs. 1(a) and 1(b). The main structure of the loudspeaker includes a membrane (nano-porous fluoro-polymer), a spacer grid, and a perforated back plate (stainless steel) with 24.15% perforation ratio. The gap between the membrane and the back plate is 100 μm. Figure 1(c) is the top-view of the loudspeaker structure, where the arrangement of the spacer grid is shown. The time-varying attraction force between the back plate and the membrane gives rise to the motion of the membrane. The device *per se* is a capacitor with capacitance varying with the distance between the membrane and the back plate, as shown in Fig. 2(a). The static attraction force (Coulomb force) between the membrane and the back plate can be calculated using the following formula:

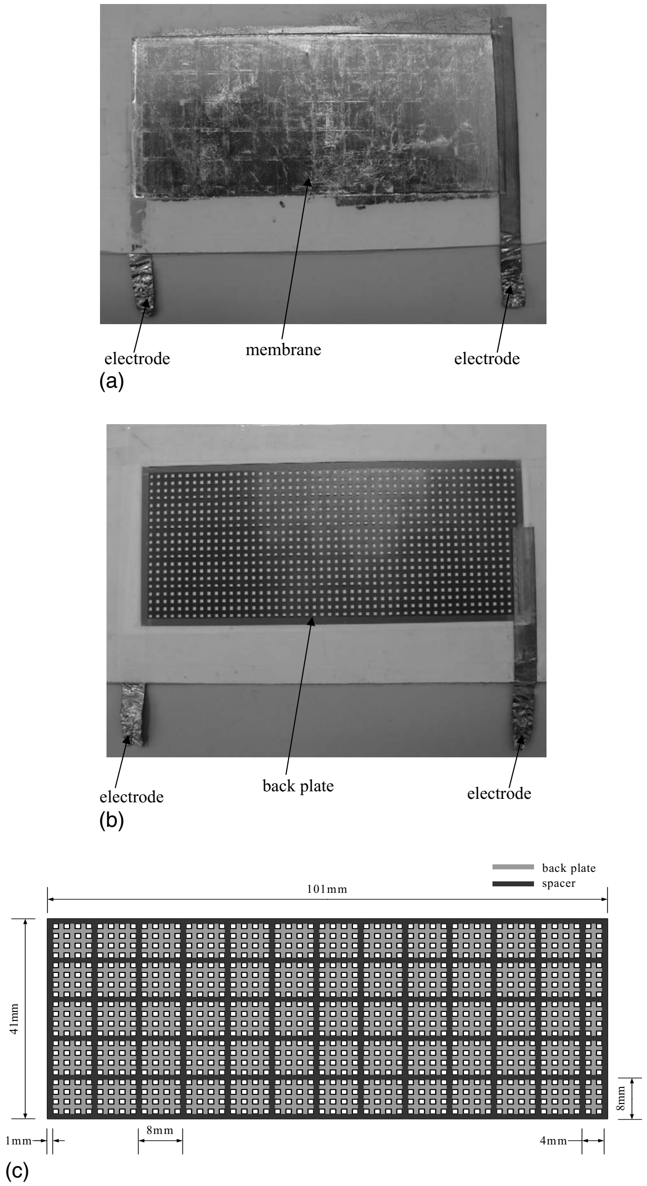

FIG. 1. The electret loudspeaker. (a) Photo (front view). (b) Photo (rear view). (c) Schematic showing the perforated back plate and the spacer grid.

$$F_0 = \frac{\varepsilon S}{2} \frac{E_0^2}{d^2}. \tag{1}$$

The dielectric constant ε is given by

$$\varepsilon = \frac{C_0 d}{S}, \tag{2}$$

where S is the area of action, E_0 is the effective dc bias voltage due to the precharged electret, d is the distance be-

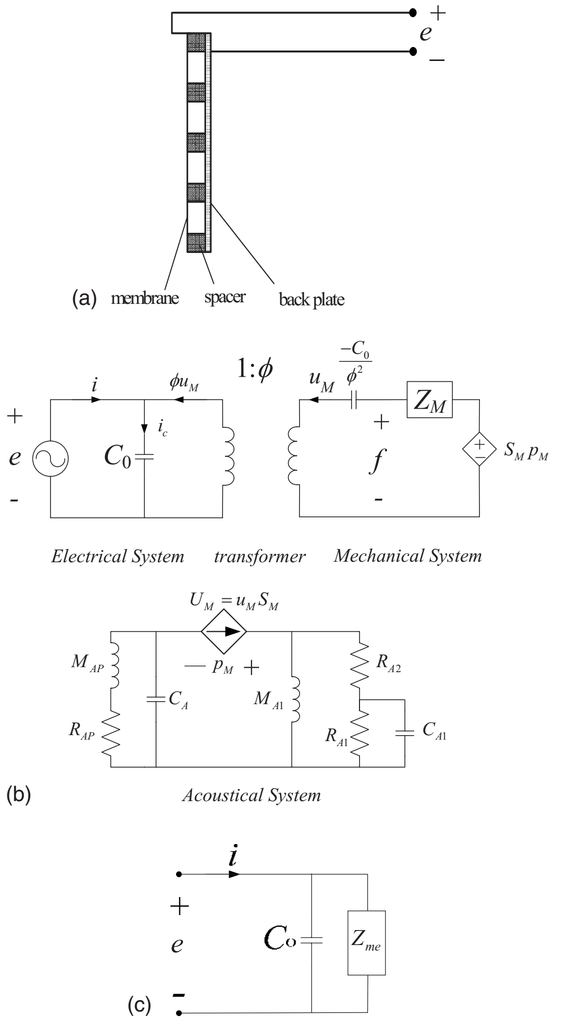

FIG. 2. The electret loudspeaker. (a) Cross-section. (b) Electroacoustic analogous circuit. (c) Analogous circuit reflected to the electrical domain.

tween the membrane and the back plate, and C_0 is the static capacitance. Assume that the membrane motion is small and the gap between the membrane and the back plate is nearly constant. The dynamic attraction force produced by the driving voltage can be approximated as

$$f = \varepsilon S \frac{E_0 e}{d^2}, \tag{3}$$

where e is the driving voltage. The electret loudspeaker can be modeled with the electroacoustic analogous circuit in Fig. 2(b). The linearized ac dynamic equation can be expressed as follows:

$$e = Z_E i + \frac{1}{j\omega C_{EM}} u_M, \tag{4}$$

$$f = \frac{1}{j\omega C_{EM}} i + Z_M u_M, \tag{5}$$

where

$$Z_E = \frac{1}{j\omega C_0}, \tag{6}$$

$$C_{EM} = \frac{\varepsilon S}{q_0}, \tag{7}$$

i is the current, u_M is the membrane velocity, Z_M is the (open-circuit) mechanical impedance of the diaphragm, Z_E is the (blocked) electrical impedance, q_0 is the static charge, and C_0 is the static capacitance. Equations (4) and (5) can also be expressed in matrix form

$$\begin{bmatrix} e \\ f \end{bmatrix} = \begin{bmatrix} Z_E & \frac{1}{j\omega C_{EM}} \\ \frac{1}{j\omega C_{EM}} & Z_M \end{bmatrix} \begin{bmatrix} i \\ u_M \end{bmatrix}. \tag{8}$$

The fact that the impedance matrix is symmetric indicates that the device is a reciprocal transducer (XDCR) with an associated transduction factor ϕ

$$\phi = \frac{C_0 E_0}{d} = \frac{C_0}{C_{EM}}. \tag{9}$$

Equations (4) and (5) can be rewritten as

$$e = \frac{1}{j\omega C_0} i_c, \tag{10}$$

$$f = \frac{\phi}{j\omega C_0} i_c + Z_{ms} u_M, \tag{11}$$

where

$$i_c = i + \phi u_M, \tag{12}$$

$$Z_{ms} = Z_M - \frac{1}{j\omega C_0/\phi^2}. \tag{13}$$

Z_{ms} is the short-circuit mechanical impedance, which is the sum of the open-circuit mechanical impedance Z_M and a negative capacitor $(-C_0/\phi^2)$. The negative capacitor can be removed if controlled sources are used in lieu of the transformer coupling.

Figure 2(c) shows the circuit with the mechanical system reflected to the electrical domain. Z_{me} is the motional impedance reflected to the electrical domain from mechanical system.

$$Z_{me} = \frac{Z_{ms}}{\phi^2}. \tag{14}$$

Since the transduction factor (ϕ) is very small, the mechanical impedance reflected to the electrical domain effectively becomes an open circuit. This is why the mechanical characteristics would not appear in the electrical impedance. In the following, we shall verify this point by using a practical measurement and FEA.

The terminal electrical impedance is measured from 400 Hz to 10 kHz using a 1.5 Vrms sweep-sine input. Figure 3(a) shows the experimental arrangement for the measurement, with symbols defined in the figure

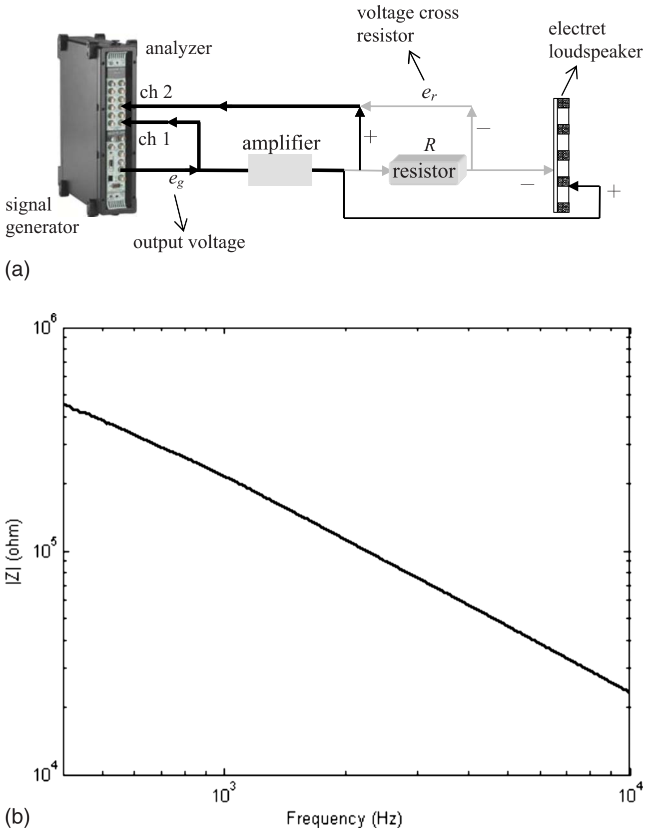

FIG. 3. (Color online) The electrical impedance measured at the terminals of the electret loudspeaker. (a) Experimental arrangement. (b) The frequency response of the measured electrical impedance.

$$Z_e = \frac{e_g G - e_r}{e_r} R, \tag{15}$$

where G is the gain of the voltage amplifier and Z_e is the terminal electrical impedance. The measured electrical impedance is shown in Fig. 3(b). It can be observed from the figure that the measured electrical impedance fits very well with the impedance of an ideal capacitor because the electromechanical coupling is weak enough to conceal the motional impedance.

$$|Z_e| = \frac{1}{\omega C_0}. \tag{16}$$

Although the mechanical parameters cannot be extracted from the measured electrical impedance, the static capacitance (C_0) can still be estimated as follows:

$$\log C_0 = -\log \omega - \log |Z_e|. \tag{17}$$

Using this formula, the static capacitance (C_0) can be estimated from the impedance log-log plot to be 7.9577 $\times 10^{-10}$ F. For the electret loudspeaker sample under test, the effective dc bias voltage (E_0) is approximately 600 V, the gap between the membrane and back plate is 0.1 mm, and the applied voltage (e) is 20 Vrms. Thus, the dielectric constant (ε) is estimated by Eq. (2) to be 1.9217×10^{-11}. The transduction factor (ϕ) calculated using Eq. (9) is 0.0048. The static and dynamic attraction forces estimated using Eqs. (1) and (3) are 1.4324 N and 0.0955 Nrms, respectively.

III. THE MODEL OF THE ELECTRET LOUDSPEAKER

As mentioned previously, the electrical impedance of the electret loudspeaker is predominantly capacitive without being influenced by the motional impedance, meaning the electromechanical coupling is extremely weak. Therefore, the parameter identification based on electrical impedance measurement is not applicable to the electret loudspeaker. An alternative approach for modeling the electret loudspeaker will be presented next.

A single-cell model, a simple model, and a full model based on FEA are developed to model the electret loudspeaker. Specifically, FEA is applied to a single-cell on the membrane in the single-cell model, and FEA is applied to the membrane in the simple model, leaving the rest of system as rigid parts, whereas FEA is applied to the entire membrane-spacer-back plate assembly in the full model. The FEA is carried out with the aid of ANSYS®.[15] In the single-cell model, the natural frequencies and the mode shapes of the membrane are calculated by the FEA modal analysis. This FEA result combined with the laser vibrometer measurement determines the material constants of the membrane. To evaluate the mechanical impedance of the membrane, the displacement frequency response of the membrane is calculated and converted into velocity by using the FEA harmonic analysis. The ratio of the external force to the mean velocity of diaphragm in mechanical system is defined as the open-circuit mechanical impedance Z_M. In order to facilitate the integration of the mechanical system, the open-circuit mechanical impedance (Z_M) defined in the following lumped-parameter two-port formalism is calculated using the complex velocity response.

$$Z_M = \frac{F}{\bar{u}}, \tag{18}$$

where F is an external force applied in the finite-element model and $\bar{u}$ denotes the mean of the complex velocity, which is obtained by the FEA harmonic analysis. Moreover, the impedance Z_{me} that is reflected from the mechanical domain to the electrical domain can be calculated by Eq. (14). Figure 4 compares $|Z_{me}|$ and the electrical impedance $|Z_E|$. It can be observed from the figure that $|Z_{me}|$ is much greater than $|Z_E|$. Therefore, the mechanical impedance reflected to the electrical domain effectively becomes an open circuit. The mechanical characteristics would not appear in the electrical impedance. This justifies the weak coupling assertion between the electrical and the mechanical systems.

The FEA simulation is based on both the simple and the full models. The mechanical impedances are calculated using harmonic analysis of FEA. The mean velocity u_M can be obtained by solving the electrical-mechanical-acoustical analogous circuits of Fig. 2(b). From a membrane with effective area S_D, the on-axis pressure at a far field distance r can be calculated using the simple source model

$$p(r) = \frac{j\rho_0 \omega U_M}{2\pi} \frac{e^{-jkr}}{r}, \tag{19}$$

where $U_M = S_D u_M$ is the volume velocity, ρ_0 is the density of air ($\rho_0 = 1.21$ kg/m^3), and k is the wave number.

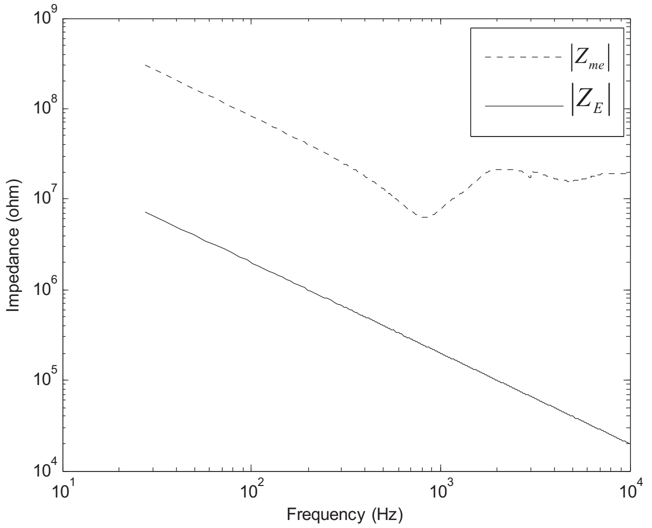

FIG. 4. The comparison between the frequency response functions of Z_{me} and Z_E.

The FEA simulation is based on both simple and full models.

A. The single-cell model and the simple model

In the simple model, it is assumed that the back plate and the spacer are rigid, while the FEA models only the flexible membrane of the electret loudspeaker. The membrane is modeled with the element "shell 41," which is a three-dimensional element allowing membrane (in-plane) stiffness but no bending (out-of-plane) stiffness. The element has four nodes and three degrees of freedom (U_x, U_y, and U_z) at each node.

TABLE I. Material properties of the electret loudspeaker.

Parameters	Spacer and back plate	Membrane
Young's modulus (N/m^2)	201×10^9	82×10^9
Poisson's ratio	0.28	0.3
Density (kg/m^3)	8000	700
Thickness (m)	17×10^{-3}	32×10^{-6}

We begin with tuning the single-cell FEA model with reference to the laser velocity response measurement. The mesh used in the finite-element model of a single-cell is shown in Fig. 5. The boundary conditions are selected such that all degrees of freedom for the outer edge of the single-cell and the displacements at the spacer are zero. Using this approach, the determined material constants of the membrane are summarized in Table I.

Next, the simple FEA model and the associated mesh of the membrane are shown in Fig. 5. The boundary conditions are selected such that all degrees of freedom for the outer edge of the membrane and the displacements at the spacer are set to be zero. The complex velocity and mechanical impedance are calculated using the FEA harmonic analysis.

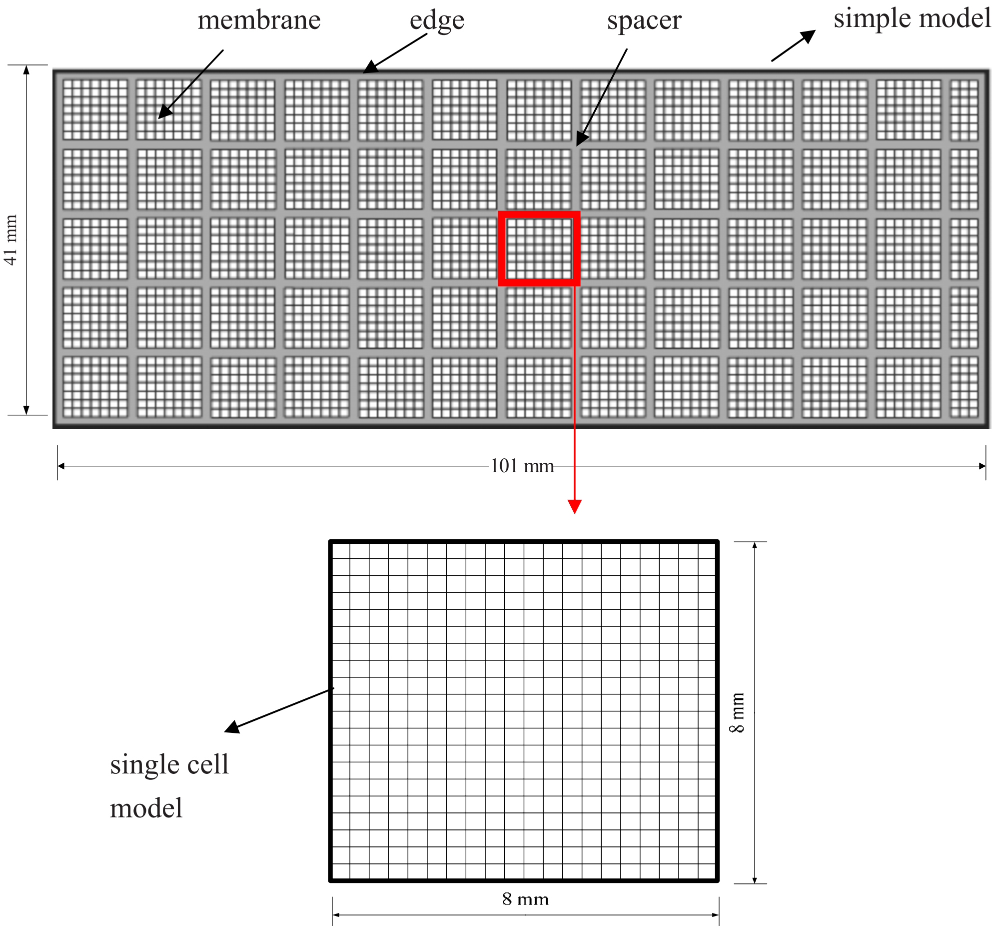

FIG. 5. (Color online) The mesh plot of the simple FEA model and single-cell FEA model of the membrane.

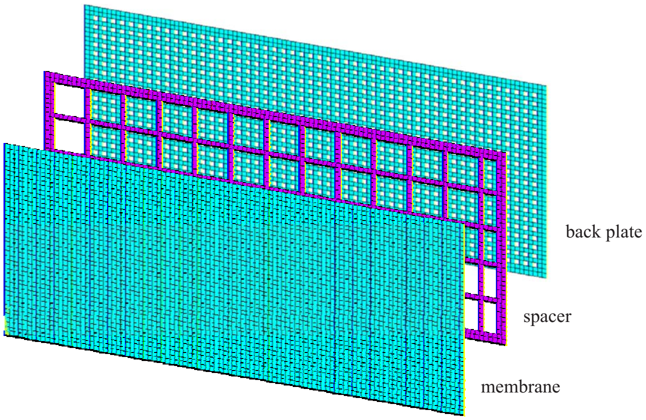

FIG. 6. (Color online) The full FEA model of the electret loudspeaker.

B. The full FEA model

In the full model, FEA is applied to the whole structure of the electret loudspeaker consisting of the membrane, the spacer grid, and the back plate.[16] The material constants assumed in the FEA are those obtained in the single-cell model (Table I). The membrane, the spacer, and the back plate are modeled using "shell 41," "solid 45," and "shell 63," respectively. The solid 45 element has eight nodes and three degrees of freedom (U_x, U_y, and U_z) at each node. The shell 63 element has four nodes and six degrees of freedom, (U_x, U_y, U_z, ROT_x, ROT_y, and ROT_z) at each node. The finite-element mesh is shown in Fig. 6. The boundary conditions are selected such that all degrees of freedom for the outer edge of the electret loudspeaker are zero. The attraction forces between the back plate and membrane are calculated using Eqs. (3) and (4). The effective mechanical impedance of the loudspeaker can also be established via the FEA harmonic analysis, as that of the simple model.

C. Modeling of the acoustical enclosure

Apart from the electrical and the mechanical systems, the modeling of the electret loudspeaker takes into account the acoustical loading resulting from the perforation of the back plate and the cavity between the back plate and the membrane. The back plate has 1000 square holes uniformly distributed over the metal sheet (perforation ratio=24.15%). The acoustical impedance of the perforation can be written as[14]

$$Z_{AP} = R_{AP} + j\omega M_{AP}, \tag{20}$$

$$R_{AP} = \frac{\rho_0}{N\pi a_h^2}\sqrt{2\omega\mu}\left[\frac{t_p}{a_h} + 2\left(1 - \frac{\pi a_h^2}{b^2}\right)\right], \tag{21}$$

$$M_{AP} = \frac{\rho_0}{N\pi a_h^2}\left[t_p + 1.7a_h\left(1 - \frac{a_h}{b}\right)\right], \tag{22}$$

where N is the number of holes of the back plate, μ is the kinematic coefficient of viscosity ($\mu = 1.56\times10^{-5}\ \mathrm{m^2/s}$), a_h is the equivalent radius of the hole, b is the spacing between the center of the adjacent holes, and t_p is the thickness of the back plate. The cavity can be modeled as acoustic compliance

$$C_A = \frac{V}{\rho_0 c^2}, \tag{23}$$

where V is the volume of cavity and c is the speed of sound ($c \approx 345$ m/s at the room temperature). The analogous circuit of the acoustical system of the electret loudspeaker is shown in Fig. 2(b). In particular, the circuit parameters to approximate radiation impedance are given by[14]

$$M_{A1} = \frac{8\rho_0}{3\pi^2 a_h}, \tag{24}$$

$$R_{A1} = \frac{0.4410\rho_0 c}{\pi a_h^2}, \tag{25}$$

$$R_{A2} = \frac{\rho_0 c}{\pi a_h^2}, \tag{26}$$

$$C_{A1} = \frac{5.94 a_h^3}{\rho_0 c^2}. \tag{27}$$

The FEA-based simulation procedure for the electret loudspeaker can be summarized as follows.

(1) Obtain the resonance frequencies and velocity response from the single-cell FEA model of membrane.
(2) Measure the membrane velocity by a laser vibrometer and compare the data with the FEA results. Tune the FEA model with the experimental data.
(3) Using the simple FEA model, obtain the complex velocity response of the membrane via FEA harmonic analysis.
(4) Using the full FEA model, obtain the complex velocity response of the membrane via FEA harmonic analysis.
(5) Calculate the mechanical impedance (Z_M) based on the complex velocity response.
(6) Calculate the acoustical impedance (Z_A) due to the perforated back plate and the cavity by the theoretical formulas and combine the mechanical impedance and the acoustical impedance to form a coupled lumped-parameter model.
(7) Calculate the volume velocity using the coupled model. Calculate the on-axis pressure based on the volume velocity response.
(8) Compare the measured on-axis pressure with the response simulated using the simple and full FEA models.

IV. NUMERICAL AND EXPERIMENTAL INVESTIGATIONS

Experimental investigation was undertaken to validate the proposed simulation models of the electret loudspeaker. The experimental arrangement for an electret loudspeaker sample is shown in Fig. 7. The electret loudspeaker is mounted on a baffle of length 1650 mm and width 1350 mm according to the standard AES2-1984 (R2003).[17] On-axis SPL and total harmonic distortion (THD) of the electret loudspeaker are measured using this setup. A 20 Vrms swept-sine signal is used to drive the electret loudspeaker in the fre-

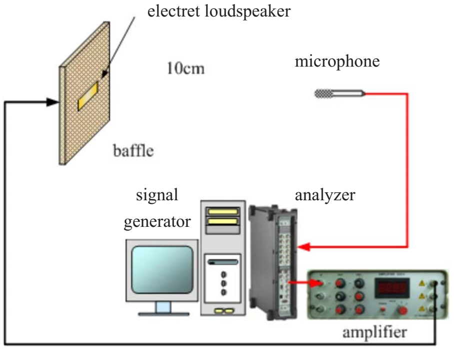

FIG. 7. (Color online) Experimental arrangement of the on-axis SPL measurement for the electret loudspeaker.

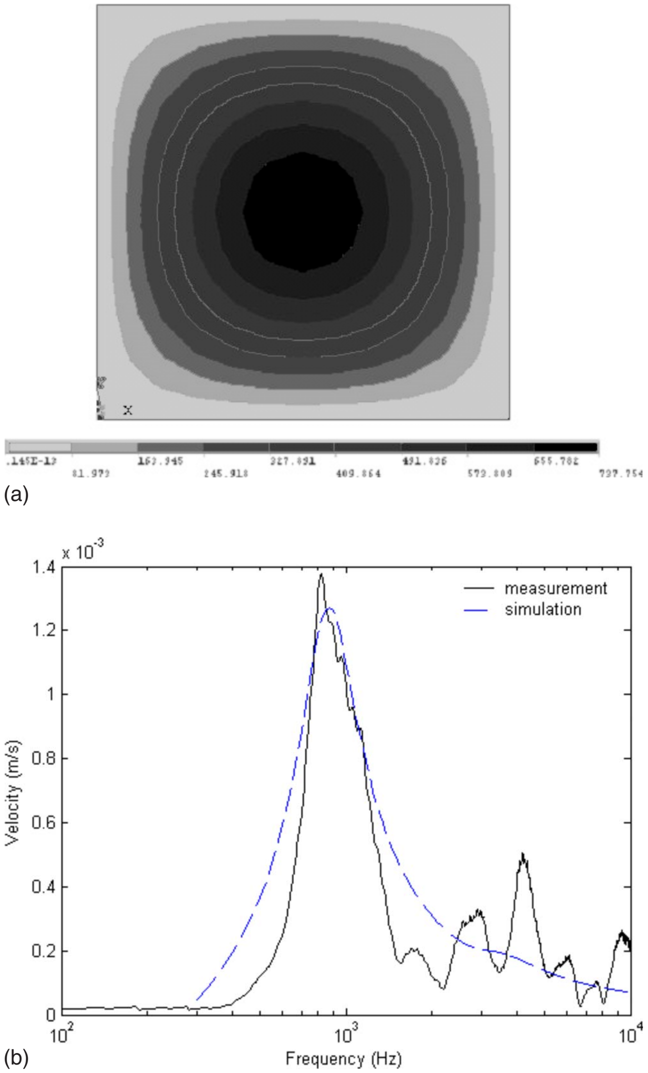

FIG. 8. (Color online) The simulation results obtained using the single-cell FEA model. (a) The fundamental mode shape of membrane. (b) Comparison of the simulated velocity response with the measured response.

quency range 20 Hz–20 kHz. The on-axis SPL is measured by using a microphone positioned at 10 cm away from the loudspeaker.

A. Comparison of the measured and the simulated responses

Simulation of the membrane response was carried out using the single-cell finite-element model. The fundamental resonance frequency predicted by the FEA modal analysis is 849.43 Hz, with the associated mode shape shown in Fig. 8(a). Using the FEM harmonic analysis, complex displacement is calculated and converted into the velocity. The fundamental resonance frequency of the velocity response measured using the laser vibrometer is 818.75 Hz, which is in close agreement with the foregoing FEA result. Figure 8(b) compares the velocity responses obtained from the experiment and simulation. Except for some minor discrepancies at high frequencies, the simulated responses (dotted lines) compare well with those of the measured results (solid lines). Some peaks of the measured frequency response may correspond to unmodeled high-order modes of the membrane. Those modes cannot be predicted by the single-cell model.

On the basis of the material constants determined in the single-cell model, simulation can be conducted for the electret loudspeaker using the simple and the full models. FEA modal analysis reveals that the fundamental resonance frequency of the simple model is 811.6 Hz, with the associated mode shape shown in Fig. 9(a). In the fundamental mode, a drumming motion appears locally in phase at every cell of the membrane. The fundamental resonance frequency found in the full model is 789.3 Hz, with the associated mode shape shown in Fig. 9(b). Clearly visible is that the entire membrane-spacer-back plate assembly moves in phase collectively in this fundamental mode.

Next, the mechanical impedance of the membrane is calculated with the aid of the FEA harmonic analysis. Combining the mechanical impedance and the acoustical impedances due to the cavity and radiation enables the estimation of the volume velocity produced by the electret loudspeaker, with which the on-axis SPL can be calculated. Figure 10 compares the on-axis SPL obtained from the simulation and the experiment, respectively. The FEA simulation is based on both the simple and the full models. It can be observed that in lower frequencies the on-axis SPL response predicted by the FEA simple model is in good agreement with the measurement. The discrepancy between the measured low-frequency response and the FEA full model could be due to the effect of the spacer and the back plate, which may induce some unmodeled low-frequency motions. In high frequencies, however, the simple model fails to capture the response due to the flexural modes of the structure. By contrast, the FEA full model seems to have predicted the high-frequency response better than the simple model. The on-axis SPL response calculated using the full FEA model matches reasonably well the measured response.

B. Nonlinear distortion

In order to assess the nonlinear distortion of the electret loudspeaker, THD is calculated from the measured frequency response of the on-axis SPL.[18]

$$\mathrm{THD} = \frac{\sqrt{p_{2f}^2 + p_{3f}^2 + \cdots + p_{nf}^2}}{p_{1f}} \times 100\,\% , \tag{28}$$

where p_{nf} is the sound pressure magnitude of the nth harmonic in the spectrum and p_{1f} is the sound pressure magni-

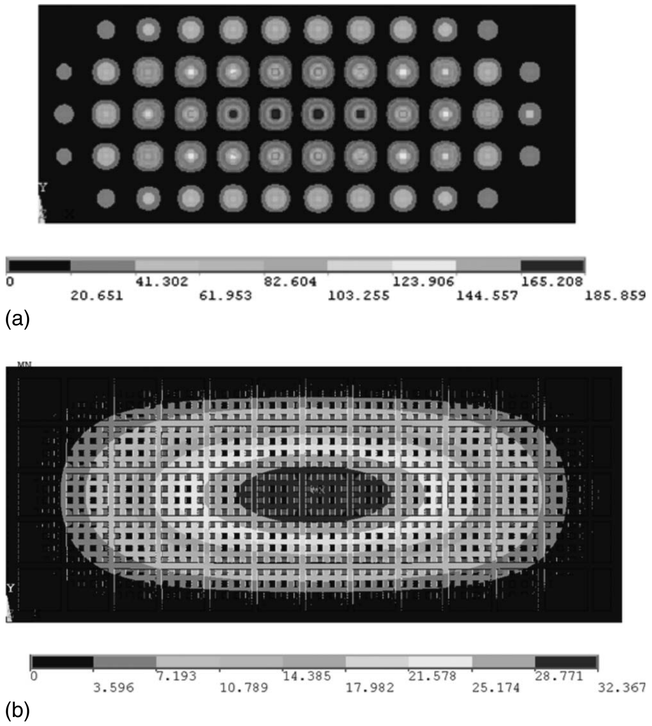

FIG. 9. The fundamental mode of the electret loudspeaker. (a) Result obtained using the simple FEA model. (b) Result obtained using the full FEA model.

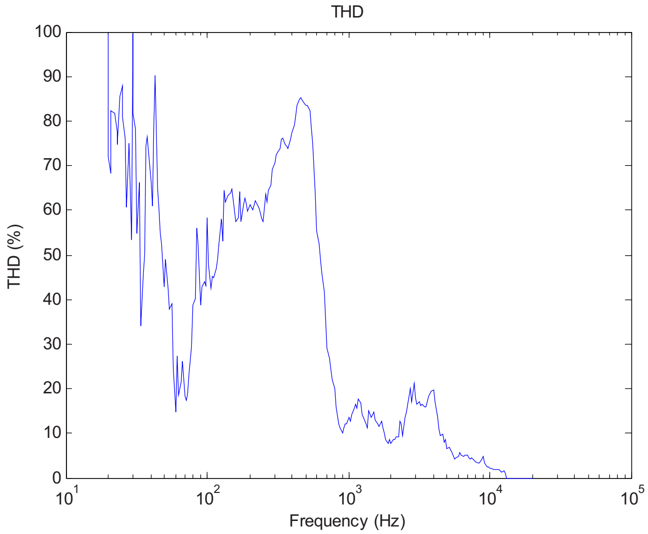

FIG. 11. (Color online) The measured THD of the electret loudspeaker.

tude of the input fundamental frequency. The measured THD of the electret loudspeaker sample is shown in Fig. 11. It can be observed that the average THD is about 17% and the THD is greater than 10% in the frequency range above the fundamental resonance frequency. The maximum THD even reaches about 20% in the range 2–3 kHz. It may be caused by the structural resonance of the loudspeaker. Informal listening tests revealed that ringing artifact is audible for some music signals involving percussion instruments.

V. CONCLUSIONS

A simulation technique for an electret loudspeaker based on the FEA alongside electroacoustical modeling has been presented in this paper. As an early attempt for the transducer of this kind, the loudspeaker element has an extremely low sensitivity. The coupling from the mechanical to the electrical circuit was simply too low to make parameter measurements based on electrical impedance measurements. Due to the weak coupling between the electrical and the mechanical systems, the electrical impedance-based parameter identification procedure is not applicable to the electret loudspeaker. An alternative approach has been presented in the paper to model the electret loudspeaker. FEA was exploited for modeling the loudspeaker with a simple model and a full model. The mechanical impedance, the volume velocity of membrane, and the on-axis pressure can be predicted using the coupled electroacoustical model.

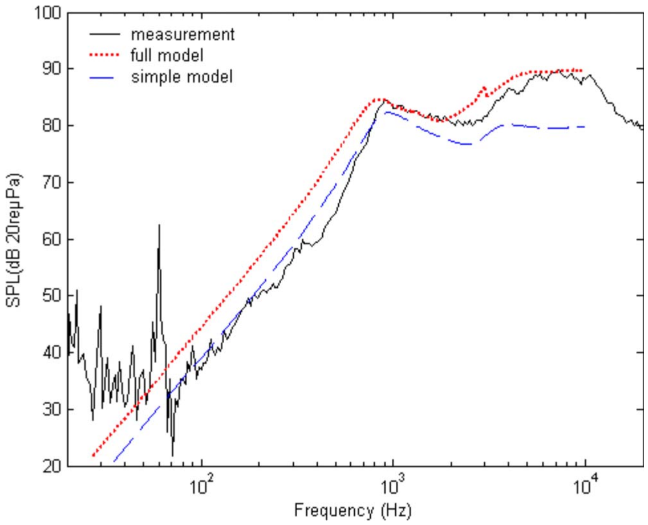

FIG. 10. (Color online) Comparison of the on-axis SPL responses of the electret loudspeaker obtained from the simulation and the experiment.

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