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Abdelhafid Kaddour[1], J. M. Rouvaen[2] and M. F. Belbachir[1]

[1]*Université des Sciences et de la Technologie d'Oran, Faculté de Génie Electrique, Département d'Electronique, B. P. 1505 Oran M'Naouar, Oran, Algérie*
[2]*Institut d'Electronique et de Microélectronique du Nord, Département Opto-Acousto-Electronique, Université de Valenciennes et du Hainaut Cambresis*
Le Mont Houy, B.P. 311, 59313 Valenciennes Cedex, France
e-mail: kaddour_a@yahoo.com

Electrodynamic loudspeaker modelling and characterization

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The modelling and the simulation software are important tools in the design process of radiator systems. Also, for the manufacturers of such systems their characterization is necessary in the quality control. This work deals with the modelling, the simulation and the characterization of an electrodynamic loudspeaker. The measured characteristics are the electrical complex impedance, the frequency response and the Harmonic Distortions (HD) including 2nd, 3rd and Total Harmonic Distortion (THD). Comparisons of computed and measured frequency response and electrical complex impedance are shown. Thiele-Small parameters are deduced from the electrical complex impedance measurement. Besides these characteristics, the visualization of sound fields is useful for understanding the directional radiation of sound emitted from such loudspeaker. For that, the transverse acoustical beam section of sound pressure field is done using acoustic intensity measurement. Matlab based programs are developed for the simulation of these characteristics and for the processing and the visualization of acoustic pressure field.

Keywords: Electrodynamic loudspeaker, modelling, simulation, characterization, measurements.

INTRODUCTION

The electrodynamic loudspeaker is an electroacoustic transducer widely used in many application areas as audio reproduction, telecommunication equipment, active noise control and active noise reduction. The knowledge of the transfer function (frequency response) between sound pressure (output) and voltage (input) is necessary in these modern control techniques. This relationship is function of the loudspeaker Thiele-Small parameters [1, 2, 3, 4]. The determination of these parameters and the different distortions has become important in the analysis and design process for loudspeaker systems manufacturers. Also, the knowledge of the directional features of the sound fields radiated by a loudspeaker is an essential characteristic of any audio system.

The present work deals with the modelling, simulation and characterization of an electrodynamic loudspeaker (diameter 12 cm), mounted in an infinite baffle. Frequency response, electrical complex impedance and the distortions were made using the Brüel & Kjær Audio Analyzer 2012 in Time Selective Response mode, which enables the free-field measurements of a loudspeaker rejecting the reflections from walls (enclosures) of an ordinary listening room. The Thiele-Small parameters are deducted from the electrical complex impedance measurement. A comparison of computed, using the electrical lumped model of loudspeaker widely used and accepted, and measured of the electrical complex impedance and frequency response are shown. Results harmonic distortions measures, including 2nd, 3rd and THD are also presented in this work.

The knowledge of the directional features of the sound fields radiated by a loudspeaker is an essential characteristic of any audio system. The numerical calculation of the acoustic field radiated from a loudspeaker is a computer-aided tool in loudspeaker design and development. The acoustic radiation from a rigid circular piston vibrating in an infinite rigid wall is a good model for studying a loudspeaker [5]. In a previous work [6, 7] the sound pressure field of a loudspeaker driven by a continuous excitation has been studied as an example. In this present work the acoustic intensity measurement technique has been used for the visualization of the sound field.

1. ELECTRODYNAMIC LOUDSPEAKER'S MODELING

The simulation part is based on the analysis of lumped element circuit model of electrodynamic transducer used by L. L. Beranek. In our simulation a similar model shown in figure 1 is used. The coupling between electrical and mechanical parts and between mechanical and acoustical parts is performed by means of the two ideal transformers respectively $(Bl:1)$ and $(1:S)$. As shown in figure 1 the three frequency dependent impedances, labelled as Z_e, Z_m and Z_a, correspond respectively to electric, mechanical, and acoustic impedances.

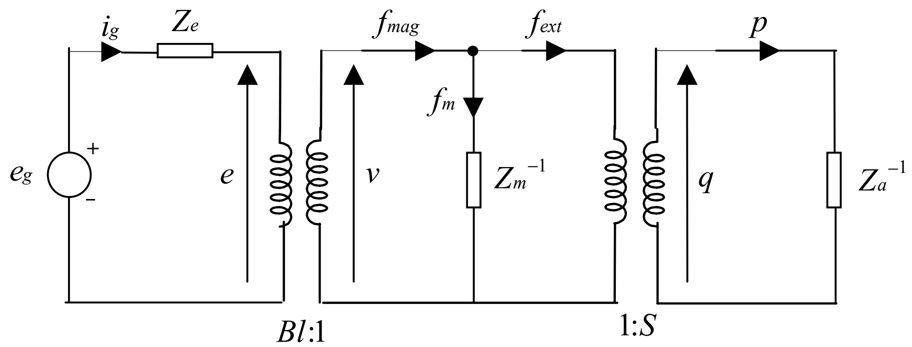

Fig. 1. Analogous circuit of moving-coil electrodynamic loudspeaker

In this figure the following designations are used:

e_g	driving voltage of the audio amplifier, V
i_g	electric current through the voice-coil, A
$Z_e = (R_r + r_g) + jL_e\omega$	complex electric impedance, Ω

$j^2 = -1$	
r_g	amplifier resistance, Ω
R_e	resistance of voice-coil, Ω
L_e	inductance of voice-coil, H
$\omega = 2\pi f$	angular frequency, rad/s
f	natural frequency variable, Hz
$e = Blv$	force induced in voice-coil, V
B	air gap flux density, T
l	length of the voice-coil wire inside magnetic field, m
v	velocity of voice-coil, m/s
$f_{mag} = Bli$	magnetic force acting on the voice-coil, N
$Z_m = R_m + j(M_m - 1/C_m\omega)$	complex mechanical impedance in mechanical ohm, Ω_m,
R_m	mechanical resistance of the driver suspension loses, Ω_m
M_m	mechanical mass of the driver diaphragm and the voice coil, kg
C_m	mechanical compliance of the suspension, m/N
f_m	mechanic force, N
f_{ext}	external force, N
q	volume velocity, m^3/s
p	acoustic pressure, N/m^2
$S = \pi a^2$	surface area of diaphragm driver, m^2, and a is radius of diaphragm, m
$Z_a = R_{ar} + jX_{ar}$	complex acoustic load impedance in acoustical ohms, Ω_a

2. ELECTRICAL COMPLEX IMPEDANCE

For low frequencies within the piston range ($f < c/2\pi a$ where c is velocity of sound in air) of the driver mounted in infinite baffle, the analogous circuit is simplified and the electrical equivalent circuit of driver is shown in figure 2:

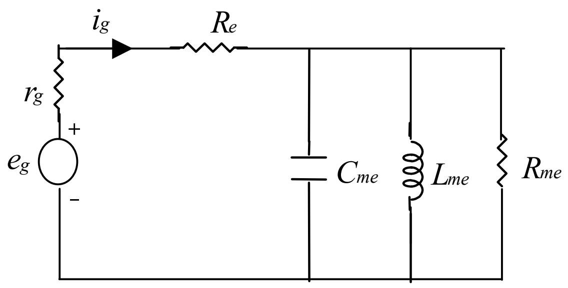

Fig. 2. Low frequencies electrical equivalent circuit of moving-coil electrodynamic driver

In this figure the following designation are used:

$C_{me} = M_m / (Bl)^2$ – electrical capacitance due to driver mass,

$L_{me} = C_m (Bl)^2$ – electrical inductance due to driver compliance,

$R_{me} = (Bl)^2 / R_m$ – electrical resistance due to driver suspension.

The impedance of the circuit, assuming $r_g \approx 0$, is expressed a follows:

$$Z_{hp} = R_e \left[(Q_m / Q_e) \frac{j(\omega/\omega_0) Q_m^{-1}}{1 - (\omega/\omega_0)^2 + j(\omega/\omega_0) Q_m^{-1}} \right], \qquad (1)$$

where $1/\omega_0^2 = C_{me} L_{me}$; $Q_m = \omega_0 R_{me} C_{me}$ is the ratio of driver electrical equivalent frictional resistance to reflected motional reactance at ω_0; $Q_e = \omega_0 R_e C_{me}$ is the ratio of voice-coil resistance to reflected motional reactance at ω_0.

The impedance measurements are performed with test setup using the Audio Analyzer 2012 and an external Amplifier type 2706 Brüel & Kjær. A resistor of 470 Ω is connected in series with the loudspeaker after the amplifier and creates constant current drive condition for a loudspeaker. Figure 3 shows impedance curve showing both magnitude (Fig. 3a) and phase (Fig. 3b) of electrical complex impedance. The frequency-varying loudspeaker impedance is the result of reactive loudspeaker elements. A slope rising with frequency is equivalent to inductive component and falling impedance is equivalent to a capacitive component (Fig. 3b). Good concordance is obtained between numerical simulated and measured results.

a) b)

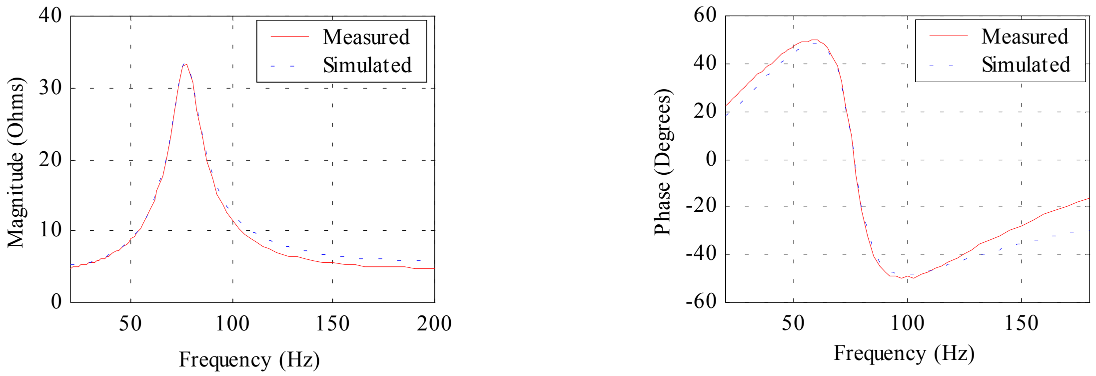

Fig. 3. Electrical complex impedance : a – amplitude ; b – phase

3. FREQUENCY RESPONSE

The frequency response of a loudspeaker is a useful and important characteristic performance because it conveys a lot of information. The frequency response is determined from acoustical analogous circuit (Fig. 4) deduced from the circuit illustrated in Fig. 1.

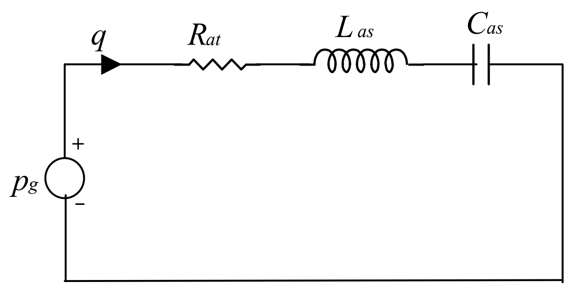

Fig. 4. Acoustical equivalent circuit of moving-coil electrodynamic driver

In this figure the following designation are used:

$p_g = e_g Bl/(r_g + R_e)S$ is the acoustic driver pressure,

$R_{at} = R_{as} + (Bl)^2/(r_g + R_e)S$; R_{as} is the acoustic resistance of driver suspension losses,

$L_{as} = M_{as}$ is the acoustic mass of driver diaphragm including air load,

C_{as} is the acoustic compliance of driver suspension.

From circuit above the expression of frequency response is deduced:

$$T(\omega) = (j\omega/\omega_0)^2/(1+(j\omega/\omega_0)^2 + (j\omega/\omega_0)Q_t^{-1}, \quad (2)$$

where $Q_t = Q_e Q_m/(Q_e + Q_m)$ is the total quality factor of the driver at ω_0.

The frequency response of a loudspeaker is measured with test setup using the Audio Analyzer 2012, the Amplifier type 2706 and a condenser microphone 4134 Brüel & Kjær. The distance separating the loudspeaker and the microphone is equal 50 cm. Results of measures as well as those simulated are shown in Fig. 5. At medium frequencies (100 Hz – 1000 Hz) we notice a good concordance between numerical simulated and measured results.

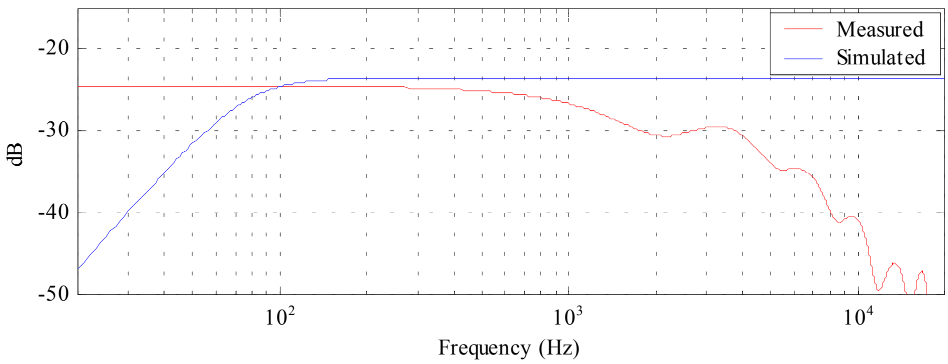

Fig. 5. Frequency response

4. DISTORTIONS

The problem of bass reproduction performance in loudspeaker is harmonic distortion. The non-linear distribution of the air-gap flux and the non-linearity of the cone suspension are the two major sources of distortion in an electrodynamic loudspeaker. Harmonic distortions, including 2^{nd}, 3^{rd} and Total Harmonic Distortion are shown in Fig. 6.

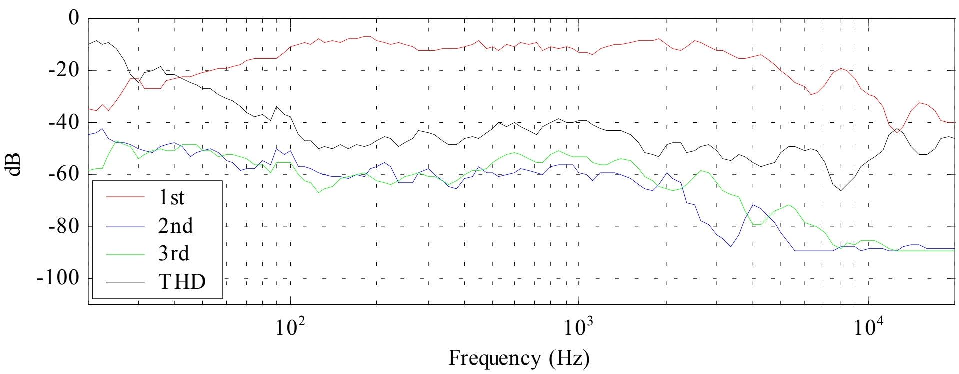

Fig. 6. Harmonic distortions

5. SPATIAL ACOUSTIC PRESSURE DISTRIBUTION

In this section the spatial distribution of radiated acoustic pressure by the loudspeaker are examined. The visualization of transverse acoustical sound pressure distribution produced by a loudspeaker is performed using the acoustic intensity measurement technique, according to the standard ISO 9614-2. This technique, using the sound intensity probe (Brüel & Kjær, type 3584) and the frequency analyzer (Brüel & Kjær type 2144), consists in measurement the acoustic intensity and acoustic pressure at different points on a parallel surface at certain distance z from the front of loudspeaker vibrating surface, following a definite sweeping procedure. Taking account of practical criteria, a measurement grid of square shape 65×65 cm ($x \times y$) including 169 surface elements forming a space matrix of 13×13 measurement points was chosen. The white noise emitted from the loudspeaker is captured by a sound intensity probe and is analyzed in 1/24 octave bands using a frequency analyzer. The experimental result given in Fig. 7 is an example of measurement using the sweep technique.

We notice that loudspeaker truly radiates the sound uniformly in all directions and behaves like a point source. The sound pressure is maximal on the axis of the loudspeaker and falls when one moves away of this axis.

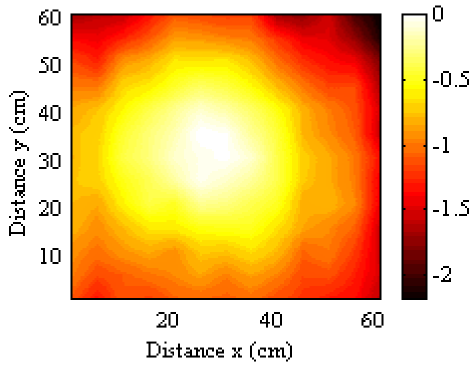

Fig. 7. Transverse profile of acoustic pressure measured at z=10 cm at 500 Hz

CONCLUSION

We presented in this article the electrodynamic loudspeaker's characteristics such the electrical complex impedance, the frequency response and the harmonic distortions including 2nd, 3rd and THD. Comparison of computed and measured electrical complex impedance and frequency response is shown. We noted that the experimental results agree with those simulated. Acoustic pressure field measurement was made using acoustic intensity measurement. Matlab based simulation programs were developed for the simulation of these characteristics and for the processing and the visualization of acoustic sound pressure field. This simulation software is very useful in order to study and design radiator systems and in Electroacoustics teaching.

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