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Experimental measurement of the nonlinearities of electrodynamic microphones for reciprocal calibration

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Abstract

This paper presents an experimental way of characterizing the nonlinearities of electrodynamic microphones used as acoustical sources. This functioning occurs for reciprocal calibration techniques. For this purpose, its electrical impedance is measured with a Wayne Kerr wedge which has an excellent precision. Moreover, it can be noted that the Thiele and Small model is used to characterize its electrical impedance. Furthermore, an experimental method based on Simplex algorithm allows us to construct polynomial laws which describe the dependence of the Thiele and Small parameters with the input voltage. The nonlinear variations obtained allow us to determine the nonlinear differential equation of the electrodynamic microphone. Then, this equation is solved numerically in order to confirm the accuracy of the polynomial laws obtained by the Simplex algorithm. The distortions are measured with a laser Doppler velocimeter and compared with the ones obtained by the numerical solving of the nonlinear differential equation. The experimental displacement spectrum is consistent with the theoretical one.

Key words: Microphone, Electrodynamic, Electrical Impedance

1 Introduction

Electrodynamic microphones are generally used either for recording voice and instruments or for reciprocal calibration techniques. They are often characterized by their directivity (omnidirectional, cardioid, supercardioid, etc...). Moreover, most of the microphones are designed as pressure microphones or pressure gradient microphones which usually leads to sound coloration. Microphone directivity is the most important property since it allows to select the sound produced by only one instrument among other instruments. However, it is not the only property which has to be taken into account. Microphone linearity is an important characteristic which is strongly linked to sound fidelity. Distortions produced by electrodynamic microphone nonlinearities is a scientific topic which is studied little. However, the most interesting studies on the microphone characterization were done by Abuelma'atti with various technologies of microphones [1]-[3] and Niewiarowicz [4][5]. Experimentally, a lot of parameters have to be taken into account and vary together according to input level. For this reason, the accurate estimation of the electrodynamic microphone main nonlinearities is difficult. Moreover, time-varying effects are also present and can modify the recording quality by amplifying or reducing distortions. The knowledge of these nonlinearities can really help designing new microphones with improved sound quality.

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21 Acutally, new developments in microphones have been performed to respond
22 to recent demands for miniaturization and high sound quality [6]-[10]. These
23 new developments are based on the traditional technology. Moreover, the non-
24 linearities observed in these new microphones have the same physical origins as
25 the nonlinearities observed in electrodynamic loudspeakers even if their func-
26 tioning is different. Therefore, the studies carried out with electrodynamic
27 loudspeakers [11]-[20] can be useful for the electrodynamic microphone ones.
28 However, electrodynamic microphones are damping controlled whereas the
29 electrodynamic loudspeakers are mainly designed to be mass controlled. Con-
30 sequently, electrodynamic microphones have a poor transient response which
31 is the most important defect. It can be noted that it is one of the main prob-
32 lems of electrodynamic microphones but this is not the only one. This paper
33 presents an experimental way of characterizing the nonlinearities of electro-
34 dynamic microphones. This experimental method is based on a very accurate
35 measurement of the electrical impedance of the electrodynamic microphone.
36 We can say that that the electrical impedance measurement of such a trans-
37 ducer is the most accurate measurement we can generally realize in a labora-
38 tory. Moreover, such a measurement is simple to perform. Consequently, the
39 experimental method presented in this paper allows us to guess what must
40 change in an electrodynamic microphone in order to improve its fidelity. In
41 addition, the electrodynamic microphone is used as an acoustical source in this
42 paper. This allows us to use important input voltages to show the nonlinear
43 effects of such transducers. Furthermore, it can be noted that the Thiele and
44 Small model [21] is used to characterize the electrical impedance of the elec-
45 trodynamic microphone. We will show that the Thiele and Small parameters
46 depend on the input voltage and consequently, some distortions are created.
47 Such distortions are measured with a laser Doppler velocimeter and predicted

48 theoretically by solving numerically the nonlinear differential equation of the
49 electrodynamic microphone. We can say that the experimental displacement
50 spectrum is consistent with the theoretical spectrum. The first section presents
51 the analytical classical model of an electrodynamic microphone and its limits.
52 The second section presents an experimental method based on the electrical
53 impedance measurement to characterize the variations of the nonlinear param-
54 eters that describe the electrodynamic microphone. This way of characterizing
55 a nonlinear system has been used in a previous paper for studying the electro-
56 dynamic loudspeaker nonlinearities[22]. The third section presents both the
57 theoretical and the experimental spectrums.

58 **2 Classical model of electrodynamic microphones and its limits**

59 An electrodynamic microphone is a transducer which transforms acoustic sig-
60 nals into electrical signals. Such an electrodynamic transducer generally in-
61 cludes a magnet motor, a rim and a diaphragm. The diaphragm vibration due
62 to the acoustical excitation (the voice for example) engenders the movement
63 of a coil which moves between two yoke pieces. Moving coil microphones use
64 the same dynamic principle as in a loudspeaker, only reversed. When sound
65 enters through the windscreen of the microphone, the sound wave moves the
66 diaphragm. When the diaphragm vibrates, the coil moves in the magnetic
67 field, producing a varying current in the coil through electromagnetic induc-
68 tion. However, it must be emphasized here that the parameter values are
69 extremely different between an electrodynamic microphone and an electrody-
70 namic loudspeaker. The apparent internal resistance R_e of an electrodynamic
71 microphone can reach 800Ω whereas it varies approximately from 2Ω to 10Ω

72 for an electrodynamic loudspeaker. Such a difference has a great influence on
 73 the dynamic of these two transducers. In addition, the equivalent damping
 74 parameter R_{ms} is rather weak for electrodynamic microphones: we can also
 75 say that its variation with input voltage generates distortions that are less im-
 76 portant than the other Thiele and Small parameters when an electrodynamic
 77 microphone is used as an acoustical source. In fact, we can say that R_{ms} rep-
 78 resents the measurement of the losses, or damping, in a driver's suspension
 79 and moving system. Consequently, as the voice-coil displacement is greater
 80 for electrodynamic loudspeakers, the losses are generally greater. This is why
 81 this parameter does not have the same influence on the acoustical response
 82 between electrodynamic microphones and electrodynamic loudspeakers. Fur-
 83 thermore, the eddy currents, commonly represented by R_{μ} , do not appear at
 84 the same frequency between an electrodynamic microphone and an electro-
 85 dynamic loudspeaker. The reason lies in the fact that the magnet dimensions
 86 and the magnetic circuit dimensions is smaller in electrodynamic microphones.
 87 Two differential equations can be used to describe the electrodynamic micro-
 88 phone. Such equations are also used for modeling electrodynamic loudspeakers
 89 [23]-[25]. The first one is given by (1).

$$90 \quad u(t) = R_e i(t) + L_e \frac{di(t)}{dt} + Bl \frac{dx(t)}{dt} \quad (1)$$

91 where $x(t)$ is the position of the coil, l is the length of the coil, L_e is the coil
 92 inductance, $i(t)$ is the coil current, Bl is the force factor, R_e is the electric re-
 93 sistor of the coil and $u(t)$ is the input voltage. The second differential equation
 94 is given by Eq.(2).

$$95 \quad M_{ms} \frac{d^2 x(t)}{dt^2} - Bli(t) = -kx(t) - R_{ms} \frac{dx(t)}{dt} \quad (2)$$

96 where M_{ms} is the mass of the diaphragm, Bl is the force factor, k is the equiva-
 97 lent stiffness of the suspensions and R_{ms} is the equivalent damping parameter.
 98 Inserting Eq.(1) in Eq.(2) leads to the complex electrical impedance given by
 99 given by Eq.(3).

$$100 \quad Z_e = R_e + jL_e w + \frac{Bl^2}{R_{ms} + jM_{ms}w + \frac{k}{jw}} \quad (3)$$

101 By taking into account the eddy currents which occur at high frequencies [26],
 102 Eq.(3) is expressed as follows (Eq.4):

$$103 \quad Z_e = R_e + \frac{jR_\mu L_e w}{jL_e w + R_\mu} + \frac{Bl^2}{R_{ms} + jM_{ms}w + \frac{k}{jw}} \quad (4)$$

104 All the parameters in Eq.(3) could be called the electrodynamic microphone
 105 parameters. As the parameters that describe the electrodynamic loudspeakers
 106 are the same, the parameters in Eq.(3) can also be called the Thiele and Small
 107 parameters. However, it must be emphasized that the parameter values are not
 108 comparable and thus, the acoustical response is very different. The main as-
 109 sumption of this classical model is that it is a linear model. In the next section,
 110 it is shown that a linear model is not sufficient for describing accurately the
 111 electrodynamic microphone behavior. Moreover, the nonlinearities are also dif-
 112 ferent between electrodynamic loudspeakers and electrodynamic microphones.
 113 For example, the voice-coil excursion of an electrodynamic loudspeaker is im-
 114 portant and generate important sound pressure levels compared to the ones
 115 produced by electrodynamic microphones used as acoustical sources. Conse-
 116 quently, the nonlinear effects that are often predominant at low frequencies
 117 for electrodynamic loudspeakers are different for electrodynamic microphones.

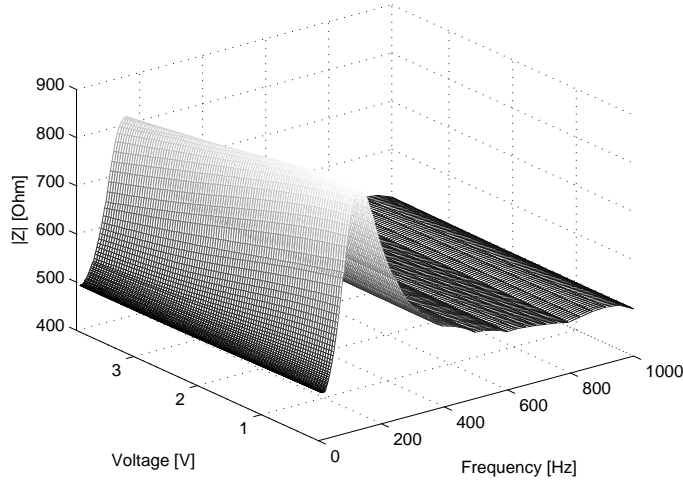


Fig. 1. Experimental three-dimensional representation of the electrical impedance magnitude of the electrodynamic microphone (voltage: 0 V;4 V)(frequency: 0 Hz;1000 Hz)($|Z|$: 400 Ω ;900 Ω)

118 *2.1 Limits of a linear electro-acoustical model*

119 This section presents the limits of the linear model for characterizing elec-
 120 trodynamic microphones. To do so, an electrodynamic microphone is placed
 121 in an anechoic chamber. An electrical impedance measurement is realized by
 122 using a Wayne Kerr wedge that has an excellent precision ($10^{-4}\Omega$). A voltage
 123 measurement is carried out with levels varying from 100mV to 4V. During our
 124 experiment, the electrodynamic microphone is used as an acoustical source.
 125 Even though this situation is rather rare, the nonlinearities determined with
 126 such an approach represent very well the main defects in electrodynamic mi-
 127 crophones. This is in fact the main aim of this paper: an accurate electrical
 128 impedance measurement can be used to estimate electrodynamic microphone
 129 nonlinearities. The electrical impedance magnitude is represented versus the
 130 input voltage and the frequency in Fig.(1) while its phase is represented in
 131 Fig. (2) A two-dimensional view allows us to see more precisely the nonlin-

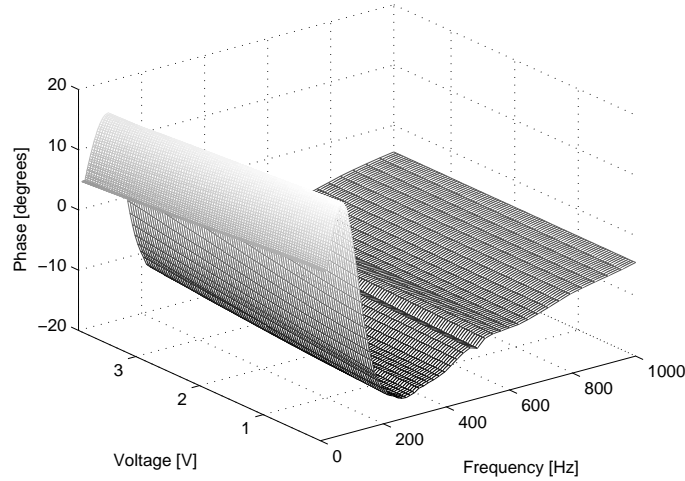


Fig. 2. Experimental three-dimensional representation of the electrical impedance phase of the electrodynamic microphone (voltage: 0 V;4 V)(frequency: 0 Hz;1000 Hz)(phase: -20 deg ;+20 deg)

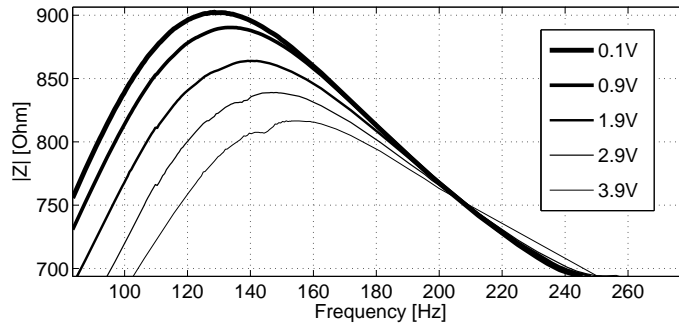


Fig. 3. Two-dimensional representation of the electrical impedance magnitude of the electrodynamic microphone (frequency: 100 Hz;260 Hz)($|Z|$: 700 Ω ; 900 Ω)

132 ear phenomena of the two previous representations (Figs. 3 and 4). Figures
 133 3 and 4 shows that the electrical impedance of the electrodynamic micro-
 134 phone depends also on input voltage. It is noted that the resonance frequency
 135 varies with respect to the input voltage; this implies that the stiffness of the
 136 suspensions or the equivalent mass depend on input voltage. In conclusion,
 137 Eq.(4) which is generally used to describe the electrodynamic microphone is
 138 not sufficient to correctly describe its nonlinear effects. Strictly speaking, all

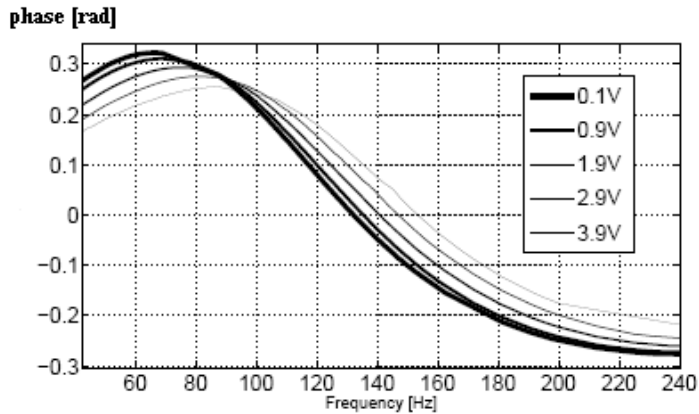


Fig. 4. Two-dimensional representation of the electrical impedance phase of the electrodynamic microphone (frequency: 60 Hz;240 Hz)(phase: -0.3 rad;+0.3 rad)

139 the parameters which define the electrical impedance (Eq.4) are a function of
 140 both input level and time. Obtaining the variation laws of these parameters
 141 is necessary in order to improve the design of electrodynamic microphones
 142 and predict the distortions created by themselves. As a consequence, a gen-
 143 eral method should be found in order to determine which parameters vary
 144 a lot with the input voltage and produce some distortions. Such a general
 145 experimental method is discussed in the next section.

146 3 Experimental method to derive the nonlinear variations of the 147 Thiele and Small parameters

148 3.1 Introduction

149 Our experimental method to derive the dependence of the Thiele and Small
 150 parameters with the input voltage is based on the electrical impedance mea-
 151 surement of the electrodynamic microphone. A real-time algorithm has been
 152 put forward to measure this impedance with a Wayne Kerr wedge that has an

153 excellent precision ($10^{-4}\Omega$). It is noted that this wedge is especially dedicated
 154 to the electrical impedance measurement. Consequently, we can say that such
 155 a measurement device allows us to have a great confidence in the experimental
 156 measurements. Our way of characterizing the electrodynamic microphone non-
 157 linearities allows us to predict precisely the distortions created by such trans-
 158 ducers. Our measurement algorithm is used in order to determine at which
 159 frequencies impedance must be measured. Basically, points must be measured
 160 when electrical impedance reaches a maximum or when impedance variation
 161 with frequency is important. In short, the electrodynamic microphone is char-
 162 acterized by its electrical impedance which, precisely measured, allows us to
 163 construct polynomial functions for each electrodynamic microphone parame-
 164 ter. The polynomial functions are determined by using Simplex algorithm and
 165 their coefficients are established by using the least mean square method. The
 166 Simplex algorithm is used to determine the coefficients of each polynomial
 167 function describing the nonlinear variations of the Thiele and Small parame-
 168 ters. The principle of this algorithm is to minimize the difference ΔZ_e between
 169 the experimental impedance and the theoretical impedance. The theoretical
 170 impedance is in fact the electrical impedance with the Thiele and Small model
 171 whose parameters are assumed to depend on input voltage. For example, the
 172 equivalent mass can be written :

$$173 \quad M_{ms}(u) = M_{ms} + \sum_{n=1}^m \tilde{\mu}_{M_{ms}}^n u^n \quad (5)$$

174 Each Thiele and Small parameter is represented like the previous form. Con-
 175 sequently, the difference ΔZ_e is expressed as follows:

$$176 \quad \Delta Z = \sum_{n=0}^{n=2} \left| \left| Z^{(exp)}(u) - Z^{(theo)}(u) \right| \right|^2 \quad (6)$$

177 where

178

$$Z^{(theo)}(u) = R_e(u) + \frac{jR_\mu(u)L_e(u)\omega}{jL_e(u)\omega + R_\mu(u)} + \frac{Bl(u)^2}{R_{ms}(u) + jM_{ms}(u)\omega + \frac{1}{jC_{ms}(u)\omega}} \quad (7)$$

179 When the algorithm converges, all the values describing the nonlinear param-
180 eters obtained are used to solve numerically the nonlinear differential equation
181 of the electrodynamic microphone. Figure 5 represents the error sheet between
182 the experimental results and the theoretical ones when the Thiele and Small
183 parameters are constant. The mean difference between the experimental and
184 the theoretical values is 6.0Ω . In this case, we did not take into account the
185 nonlinear variations of the Thiele and Small parameters determined by the
186 Simplex algorithm. Figure (6) represents the error sheet between the experi-
187 mental results and the theoretical one when the variations of the Thiele and
188 Small parameters are taken into account. The mean difference between the ex-
189 perimental and the theoretical values is 2.9Ω . As a consequence, the improve-
190 ment of the electrodynamic microphone model is only possible if the nonlinear
191 variations of the Thiele and Small parameters are taken into account.

192 3.2 Variations of the Thiele and Small parameters

193 This section discusses the sensitivity of the Thiele and Small parameters to
194 the least mean square method. To do so, we assume that only one parameter
195 varies at a time (though the other Thiele and Small parameters are constant).
196 By using our least square method based on the simplex method, we determine
197 the difference of the impedance (magnitude and phase) between the model
198 with constant parameters and the model with one varying parameter. This

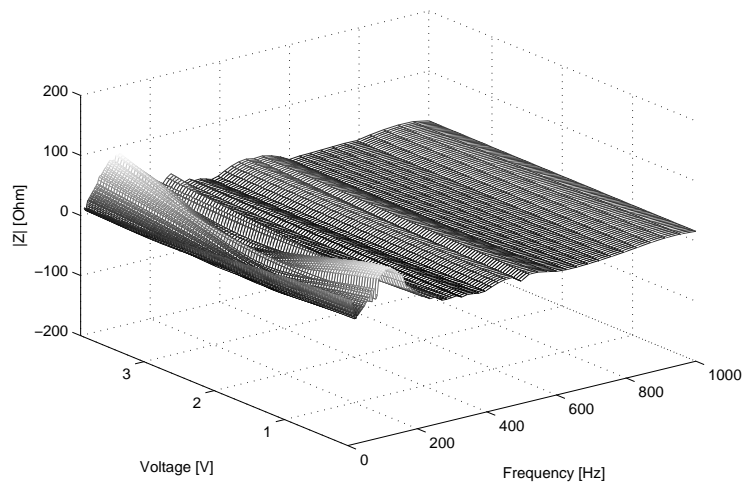


Fig. 5. Three-dimensional representation of the difference between the experimental impedance and the theoretical impedance ; the theoretical impedance is based on the Thiele and Small model with constant parameters (voltage: 0 V;4 V)(frequency: 0 Hz;1000 Hz)($|Z|$: -200 Ω ;+200 Ω)

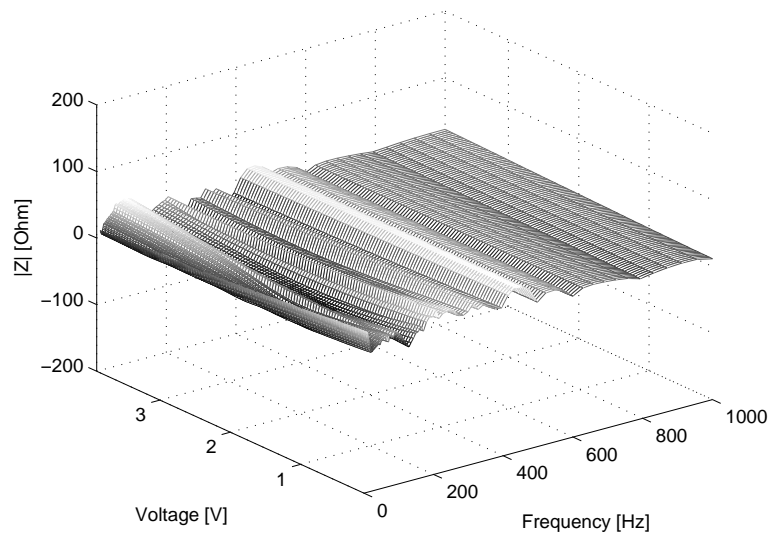


Fig. 6. Three-dimensional representation of the difference between the experimental impedance and the theoretical impedance ; the theoretical impedance is based on the Thiele and Small model with variable parameters (voltage: 0 V;4 V)(frequency: 0 Hz;1000 Hz)($|Z|$: -200 Ω ;+200 Ω)

Parameter	Law of variation	sensitivity
Re	490.1	
Le	$0.0023 + 0.002u + 0.06u^2$	15.1%
Bl	$13.2 - 15.1u + 8.09u^2$	23%
Rms	$0.25 + 0.81u - 0.021u^2$	4.7%
Mms	$0.00025 - 0.0014u + 0.0036u^2$	18.1%
k	$171.28 - 50.2u + 1018u^2$	2.1%
R_μ	48.1	

Table 1

Laws of variations of the Thiele and Small parameters

199 difference allows us to determine the sensitivity of each Thiele and Small pa-
200 rameter. Table 1 presents the laws of variations of Thiele and Small parameters
201 determined with our three-dimensional least mean square method.

202 It can be noted that the parameter that is the most sensitive to the least mean
203 square algorithm is the force factor Bl . In addition, we see that the equivalent
204 inductance L_e is also sensitive. This implies that the magnetic circuit could be
205 improved. In fact, it is well-known that the iron in magnetic circuits generates
206 nonlinearities because of its saturation and its hysteresis losses. This is the
207 reason why it can be interesting to design ironless magnetic loudspeakers [20].

208 3.3 Obtaining the nonlinear differential equation of the electrodynamic mi-
 209 crophone

210 This section presents a method to obtain the nonlinear differential equation
 211 of the electrodynamic microphone. In fact, this nonlinear differential equa-
 212 tion is the same as the one of the electrodynamic loudspeaker because the
 213 electrodynamic microphone is used as an acoustical source. In this paper, the
 214 nonlinear differential equation of the electrodynamic microphone is obtained
 215 by taking into account the variations of the Thiele and Small parameters.
 216 These variations are obtained in the previous section by using both the Sim-
 217 plex algorithm with the least mean square criteria. Furthermore, we neglect
 218 here the unstationary effects (R_e increases in time due to the Joule effect).
 219 The first step for obtaining this nonlinear differential equation is to drop the
 220 parameter $i(t)$ from the two equations (1) and (2). From (2), $i(t)$ can also be
 221 written as follows:

$$222 \quad i(t) = \frac{1}{Bl} \left(M_{ms} \frac{d^2x(t)}{dt^2} + R_{ms} \frac{dx(t)}{dt} + kx(t) \right) \quad (8)$$

223 By using (8) and 1, we deduct :

224

$$225 \quad u(t) = \frac{R_e}{Bl} \left(M_{ms} \frac{d^2x(t)}{dt^2} + R_{ms} \frac{dx(t)}{dt} + kx(t) \right) \\
 + Bl \frac{dx(t)}{dt} + \frac{L_e}{Bl} \left(M_{ms} \frac{d^3x(t)}{dt^3} + R_{ms} \frac{d^2x(t)}{dt^2} + k \frac{dx(t)}{dt} \right) \quad (9)$$

225 The previous equation can also be written in the following form :

$$226 \quad u(t) = a \frac{d^3x(t)}{dt^3} + b \frac{d^2x(t)}{dt^2} + c \frac{dx(t)}{dt} + dx(t) \quad (10)$$

227 with

$$228 \quad a = \frac{M_{ms}L_e}{Bl} \quad (11)$$

$$229 \quad b = \frac{(M_{ms}R_e + R_{ms}L_e)}{Bl} \quad (12)$$

$$230 \quad c = \frac{(R_eR_{ms} + Bl^2 + kL_e)}{Bl} \quad (13)$$

$$231 \quad d = \frac{kR_e}{Bl} \quad (14)$$

232 We can also write the previous relations in the frequency domain so that (10)
233 becomes :

$$234 \quad U = a(jw)^3X + b(jw)^2X + c(jw)X + dX \quad (15)$$

235 Thus, we deduct that there is a bijective relation between U and X:

$$236 \quad U = X (A(jw)^3 + B(jw)^2 + C(jw) + D) \quad (16)$$

237 Thus

$$238 \quad U = \chi X \quad (17)$$

239 where $\chi = (A(jw)^3 + B(jw)^2 + C(jw) + D)$. In the previous section, we stud-
240 ied the fact that the five Small signal parameters depended on input voltage.
241 We deduct that these parameters can also be written as a function of the
242 voice coil position X . Therefore, the parameters a , b , c and d in 10 become
243 $a(x)$, $b(x)$, $c(x)$ and $d(x)$ in the nonlinear differential equation of the electro-
244 dynamic microphone. It is to be noted that solving this nonlinear differential
245 equation is rather difficult because the denominator is not constant. It can

246 be noted that this equation must be solved numerically in order to determine
247 the distortions created by an electrodynamic microphone. In fact, the distor-
248 tions created by a nonlinear system can be determined either analytically by
249 using for example a Taylor series expansion or numerically. In the case of the
250 electrodynamic microphone, we have chosen to solve numerically its nonlinear
251 differential equation with Mathematica. This allows us to confirm the experi-
252 mental displacement spectrum measured with the laser Doppler velocimeter.

253 *3.4 Comparison between the theoretical displacement spectrum and the ex-* 254 *perimental displacement spectrum*

255 A way of obtaining the theoretical displacement spectrum is to solve numer-
256 ically the nonlinear differential equation of the electrodynamic microphone.
257 This can be done for example in the time-domain by assuming that the elec-
258 trodynamic microphone generates only harmonics that are multiple of the
259 fundamental harmonic ($w, 2w, 3w$). This is a simplifying assumption because
260 input voltage owns in reality many terms so that other typical nonlinear phe-
261 nomena appear (intermodulations). In short, we assume the solution of the
262 nonlinear differential equation of the electrodynamic microphone to be as the
263 following form:

$$\begin{aligned} x(t) = & a_1 \cos(wt) + a_2 \sin(wt) + a_3 \cos(2wt) + a_4 \sin(2wt) \\ & + a_5 \cos(3wt) + a_6 \sin(3wt) \end{aligned} \tag{18}$$

264 The parameters a_1, a_2, a_3, a_4, a_5 and a_6 are determined numerically and are
265 given in Table 2.

Coefficient	Value
a_1	5.210^{-3}
a_2	0.8310^{-3}
a_3	2.4510^{-12}
a_4	4.1810^{-13}
a_5	8.8310^{-16}
a_6	6.1210^{-16}

Table 2

Values of the coefficients given in Eq. (18) : these coefficients have been determined with the explicit Runge Kutta method (numerical solving of the nonlinear differential equation of the electrodynamic microphone)

266 *3.5 Experimental and theoretical displacement spectrums*

267 This section presents a comparison between the experimental displacement
268 spectrum of the electrodynamic microphone which has been obtained by us-
269 ing a laser Doppler velocimeter and the theoretical displacement spectrum
270 obtained by using the solution given in Eq. (18). The experimental and theo-
271 retical values are given in table 3. Moreover, the results obtained are plotted
272 in Fig. 7. The theoretical displacement spectrum is consistent with the ex-
273 perimental displacement spectrum. Consequently, we deduct that the experi-
274 mental way of characterizing the electrodynamic microphone with its electrical
275 impedance allows us to precisely estimate the nonlinear variations of the Small
276 signal parameters with the input voltage.

	H1	H2	H3
$\log[x_{exp}]$	-5.17	-11.89	-14.1
$\log[x_{theo}]$	-5.24	-12.08	-15.3

Table 3

Values of the harmonics created by the electrodynamic microphone ; H1 corresponds to the fundamental, H2 is the harmonic two and H3 is the harmonic three

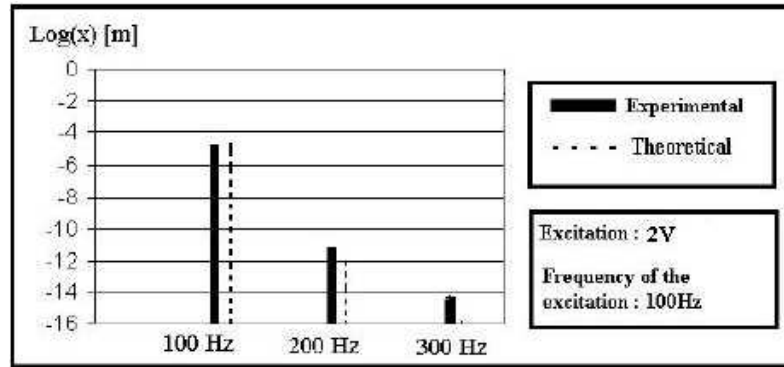


Fig. 7. Experimental and Theoretical spectrums of the electrodynamic microphone

277 4 Conclusion

278 In this paper, we studied the nonlinear effects of electrodynamic microphones
279 that occur when they are used as acoustical sources. This functioning occurs
280 in reciprocal calibration techniques. An experimental method, based on a very
281 precise electrical impedance measurement allows us to put forward a measure-
282 ment algorithm which is used to acquire as many points as possible. This mea-
283 surement algorithm has been put forward in the case of the nonlinear study of
284 electrodynamic loudspeakers. Taking into account the variations of the Small
285 signal parameters with the input voltage allows us to improve significantly the
286 model of the electrodynamic microphone. The variations of the Small signal
287 parameters generate any distortions. These distortions can be predicted by

288 solving numerically the nonlinear differential equation of the electrodynamic
289 microphone. The comparison between the theoretical displacement spectrum
290 and the experimental displacement spectrum shows a very good agreement at
291 low frequencies.

References

- [1] M. T. Abuelma'atti, "Improved analysis of the electrically manifested distortions of condenser microphones," *Applied Acoustics*, vol. 64, pp. 471–480, May 2003.
- [2] M. T. Abuelma'atti, "Harmonic and intermodulation distortion in electret microphones," *Applied Acoustics*, vol. 34, no. 1, pp. 1–6, 1991.
- [3] M. T. Abuelma'atti, "Large signal performance of micromachined silicon condenser microphones," *Applied Acoustics*, vol. 68, pp. 1286–1296, October 2007.
- [4] M. Niewiarowicz, "Investigations into the transduction properties of dynamic microphone membranes subjected to transients," *Applied Acoustics*, vol. 22, no. 3, pp. 177–183, 1987.
- [5] M. Niewiarowicz, "Determination of active compliance of dome type microphone membranes by using the indicator diagrams method," *Journal of Sound and Vibration*, vol. 182, no. 4, pp. 589–594, 1995.
- [6] S.-M. Hwang, H.-J. Lee, K.-S. Hong, B.-S. Kang, and G.-Y. Hwang, "New development of combined permanent-magnet type microspeakers used for cellular phones," *IEEE Trans. Magn*, vol. 41, no. 5, pp. 2000–2003, 2005.
- [7] P. C. P. Chao, C. W. Chiu, and Y. Hsu-Pang, "Magneto-electrodynamical modeling and design of a microspeaker used for mobile phones with

- considerations of diaphragm corrugation and air closures,” *IEEE Trans. Magn.*, vol. 43, no. 6, pp. 2585–2587, 2007.
- [8] P. C. P. Chao and S.-C. Wu, “Optimal design of magnetic zooming mechanism used in cameras of mobile phones via genetic algorithm,” *IEEE Trans. Magn.*, vol. 43, no. 6, pp. 2579–2581, 2007.
- [9] E. Sadikog, “A laser pistonphone based on self-mixing interferometry for the absolute calibration of measurement microphones,” *Applied Acoustics*, vol. 65, no. 9, pp. 833–840, 2004.
- [10] T. Musha and J. I. Taniguchi, “Measurement of sound intensity using a single moving microphone,” *Applied Acoustics*, vol. 66, no. 5, pp. 579–589, 2005.
- [11] E. R. Olsen and K. B. Christensen, “Nonlinear modeling of low frequency loudspeakers- a more complete model,” in *100th convention, Copenhagen*, no. 4205, Audio Eng. Soc., 1996.
- [12] J. W. Noris, “Nonlinear dynamical behavior of a moving voice coil,” in *105th convention, San Francisco*, no. 4785, Audio Eng. Soc., 1998.
- [13] A. Dobrucki, “Nontypical effects in an electrodynamic loudspeaker with a nonhomogeneous magnetic field in the air gap and nonlinear suspension,” *J. Audio Eng. Soc.*, vol. 42, pp. 565–576, 1994.
- [14] M. R. Gander, “Dynamic linearity and power compression in moving-coil loudspeaker,” *J. Audio Eng. Soc.*, pp. 627–646, September 1986.
- [15] M. R. Gander, “Moving-coil loudspeaker topology as an indicator of linear excursion capability,” *J. Audio Eng. Soc.*, vol. 29, 1981.
- [16] W. M. Leach, “Loudspeaker voice-coil inductance losses : Circuit models, parameter estimation and effect on frequency response,” *J. Audio Eng. Soc.*, pp. 442–449, 2002.

- [17] J. R. Wright, "An empirical model for loudspeaker motor impedance," *J. Audio Eng. Soc.*, pp. 749–754, October 1990.
- [18] W. Klippel, "Loudspeaker nonlinearities - cause, parameters, symptoms," *J. Audio Eng. Soc.*, vol. 54, pp. 907–939, 2006.
- [19] R. Ravaud, G. Lemarquand, V. Lemarquand, and C. Depollier, "Ironless loudspeakers with ferrofluid seals," *Archives of Acoustics*, vol. 33, no. 4, pp. 3–10, 2008.
- [20] G. Lemarquand, "Ironless loudspeakers," *IEEE Trans. Magn.*, vol. 43, no. 8, pp. 3371–3374, 2007.
- [21] R. H. Small, "Closed-box loudspeaker systems, part1: Analysis," *J. Audio Eng. Soc.*, vol. 20, no. 12, pp. 798–808, 1972.
- [22] R. Ravaud, G. Lemarquand, and T. Roussel, "Time-varying nonlinear modeling of electrodynamic loudspeakers," *Applied Acoustics*, vol. 70, no. 3, pp. 450–458, 2009.
- [23] A. N. Thiele, "Loudspeakers in vented boxes, part i," *J Audio Eng Soc*, vol. 19, pp. 382–392, 1971.
- [24] A. N. Thiele, "Loudspeakers in vented boxes, part ii," *J Audio Eng Soc*, vol. 19, pp. 471–483, 1971.
- [25] R. H. Small, "Direct-radiator loudspeaker system analysis," *J. Audio Eng. Soc.*, vol. 20, no. 6, pp. 383–395, 1972.
- [26] J. Vanderkooy, "A model of loudspeaker driver impedance incorporating eddy currents in the pole structure," *J. Audio Eng. Soc.*, vol. 37, pp. 119–128, March 1989.