Experimental measurement of the nonlinearities of electrodynamic microphones

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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

PACS: 43-38 Ja

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, cardiod, supercardiod, 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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Acutally, new developments in microphones have been performed to respond to recent demands for miniaturization and high sound quality [6]-[10]. These new developments are based on the traditional technology. Moreover, the nonlinearities observed in these new microphones have the same physical origins as the nonlinearities observed in electrodynamic loudspeakers even if their functioning is different. Therefore, the studies carried out with electrodynamic loudspeakers [11]-[20] can be useful for the electrodynamic microphone ones. However, electrodynamic microphones are damping controlled whereas the electrodynamic loudspeakers are mainly designed to be mass controlled. Consequently, electrodynamic microphones have a poor transient response which is the most important defect. It can be noted that it is one of the main problems of electrodynamic microphones but this is not the only one. This paper presents an experimental way of characterizing the nonlinearities of electrodynamic microphones. This experimental method is based on a very accurate measurement of the electrical impedance of the electrodynamic microphone. We can say that that the electrical impedance measurement of such a transducer is the most accurate measurement we can generally realize in a laboratory. Moreover, such a measurement is simple to perform. Consequently, the experimental method presented in this paper allows us to guess what must change in an electrodynamic microphone in order to improve its fidelity. In addition, the electrodynamic microphone is used as an acoustical source in this paper. This allows us to use important input voltages to show the nonlinear effects of such transducers. Furthermore, it can be noted that the Thiele and Small model [21] is used to characterize the electrical impedance of the electrodynamic microphone. We will show that the Thiele and Small parameters depend on the input voltage and consequently, some distortions are created. Such distortions are measured with a laser Doppler velocimeter and predicted theoretically by solving numerically the nonlinear differential equation of the electrodynamic microphone. We can say that the experimental displacement spectrum is consistent with the theoretical spectrum. The first section presents the analytical classical model of an electrodynamic microphone and its limits. The second section presents an experimental method based on the electrical impedance measurement to characterize the variations of the nonlinear parameters that describe the electrodynamic microphone. This way of characterizing a nonlinear system has been used in a previous paper for studying the electrodynamic loudspeaker nonlinearities[22]. The third section presents both the theoretical and the experimental spectrums.

2 Classical model of electrodynamic microphones and its limits

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

for an electrodynamic loudspeaker. Such a difference has a great influence on the dynamic of these two transducers. In addition, the equivalent damping parameter R_{ms} is rather weak for electrodynamic microphones: we can also say that its variation with input voltage generates distortions that are less important than the other Thiele and Small parameters when an electrodynamic microphone is used as an acoustical source. In fact, we can say that R_{ms} represents the measurement of the losses, or damping, in a driver's suspension and moving system. Consequently, as the voice-coil displacement is greater for electrodynamic loudspeakers, the losses are generally greater. This is why this parameter does not have the same influence on the acoustical response between electrodynamic microphones and electrodynamic loudspeakers. Furthermore, the eddy currents, commonly represented by R_μ, do not appear at the same frequency between an electrodynamic microphone and an electrodynamic loudspeaker. The reason lies in the fact that the magnet dimensions and the magnetic circuit dimensions is smaller in electrodynamic microphones. Two differential equations can be used to describe the electrodynamic microphone. Such equations are also used for modeling electrodynamic loudspeakers [23]-[25]. The first one is given by (1).

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

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

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

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

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

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

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

All the parameters in Eq.(3) could be called the electrodynamic microphone parameters. As the parameters that describe the electrodynamic loudspeakers are the same, the parameters in Eq.(3) can also be called the Thiele and Small parameters. However, it must be emphasized that the parameter values are not comparable and thus, the acoustical response is very different. The main assumption of this classical model is that it is a linear model. In the next section, it is shown that a linear model is not sufficient for describing accurately the electrodynamic microphone behavior. Moreover, the nonlinearities are also different between electrodynamic loudspeakers and electrodynamic microphones. For example, the voice-coil excursion of an electrodynamic loudspeaker is important and generate important sound pressure levels compared to the ones produced by electrodynamic microphones used as acoustical sources. Consequently, the nonlinear effects that are often predominant at low frequencies for electrodynamic loudspeakers are different for electrodynamic microphones.

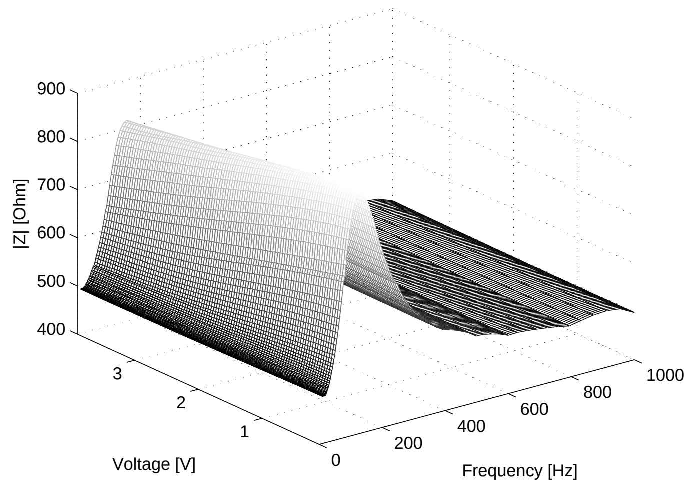

Fig. 1. Experimental three-dimensional representation of the electrical impedance magnitude of the electrodynamic microphone (voltage: 0 V;4 V)(frequency: 0 Hz;1000 Hz)($|Z|$: 400Ω;900Ω)

2.1 Limits of a linear electro-acoustical model

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

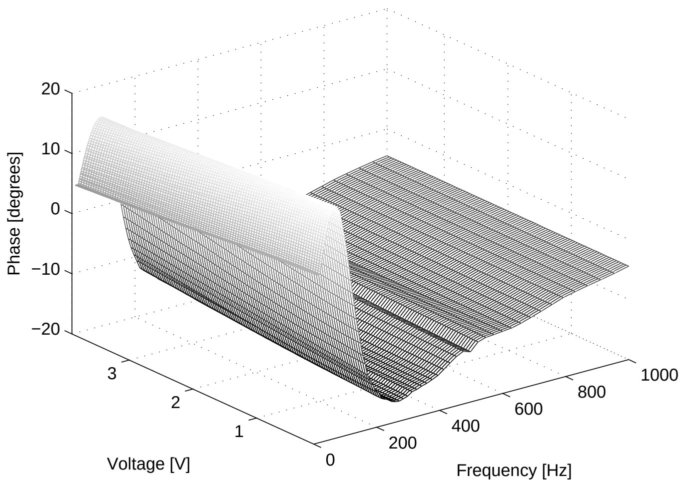

Fig. 2. Experimental three-dimensional representation of the electrical impedance phase of the electrodynamic microphone (voltage: 0 V;4 V)(frequency: 0 Hz;1000 Hz)(phase: -20 deg ;+20 deg)

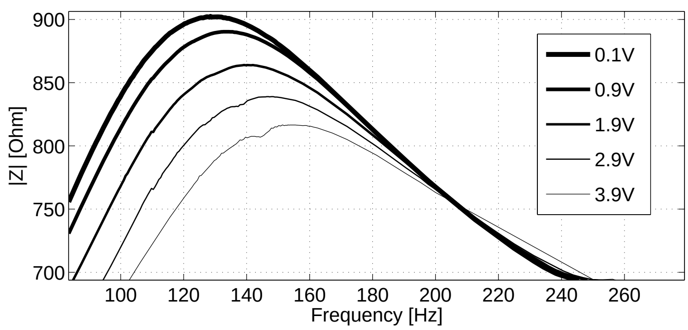

Fig. 3. Two-dimensional representation of the electrical impedance magnitude of the electrodynamic microphone (frequency: 100 Hz;260 Hz)($|Z|$: 700 Ω; 900 Ω)

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

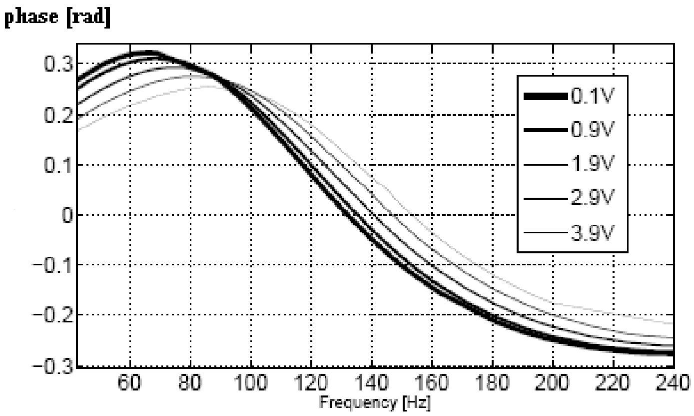

Fig. 4. Two-dimensional representation of the electrical impedance phase of the electrodynamic microphone (frequency: 60 Hz;240 Hz)(phase: -0.3 rad;+0.3 rad)

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

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

3.1 Introduction

Our experimental method to derive the dependence of the Thiele and Small parameters with the input voltage is based on the electrical impedance measurement of the electrodynamic microphone. A real-time algorithm has been put forward to measure this impedance with a Wayne Kerr wedge that has an excellent precision ($10^{-4}\Omega$). It is noted that this wedge is especially dedicated to the electrical impedance measurement. Consequently, we can say that such a measurement device allows us to have a great confidence in the experimental measurements. Our way of characterizing the electrodynamic microphone nonlinearities allows us to predict precisely the distortions created by such transducers. Our measurement algorithm is used in order to determine at which frequencies impedance must be measured. Basically, points must be measured when electrical impedance reaches a maximum or when impedance variation with frequency is important. In short, the electrodynamic microphone is characterized by its electrical impedance which, precisely measured, allows us to construct polynomial functions for each electrodynamic microphone parameter. The polynomial functions are determined by using Simplex algorithm and their coefficients are established by using the least mean square method. The Simplex algorithm is used to determine the coefficients of each polynomial function describing the nonlinear variations of the Thiele and Small parameters. The principle of this algorithm is to minimize the difference ΔZ_e between the experimental impedance and the theoretical impedance. The theoretical impedance is in fact the electrical impedance with the Thiele and Small model whose parameters are assumed to depend on input voltage. For example, the equivalent mass can be written :

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

Each Thiele and Small parameter is represented like the previous form. Consequently, the difference ΔZ_e is expressed as follows:

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

where

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

When the algorithm converges, all the values describing the nonlinear parameters obtained are used to solve numerically the nonlinear differential equation of the electrodynamic microphone. Figure 5 represents the error sheet between the experimental results and the theoretical ones when the Thiele and Small parameters are constant. The mean difference between the experimental and the theoretical values is 6.0Ω. In this case, we did not take into account the nonlinear variations of the Thiele and Small parameters determined by the Simplex algorithm. Figure (6) represents the error sheet between the experimental resuts and the theoretical one when the variations of the Thiele and Small parameters are taken into account. The mean difference between the experimental and the theoretical values is 2.9Ω. As a consequence, the improvement of the electrodynamic microphone model is only possible if the nonlinear variations of the Thiele and Small parameters are taken into account.

3.2 Variations of the Thiele and Small parameters

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

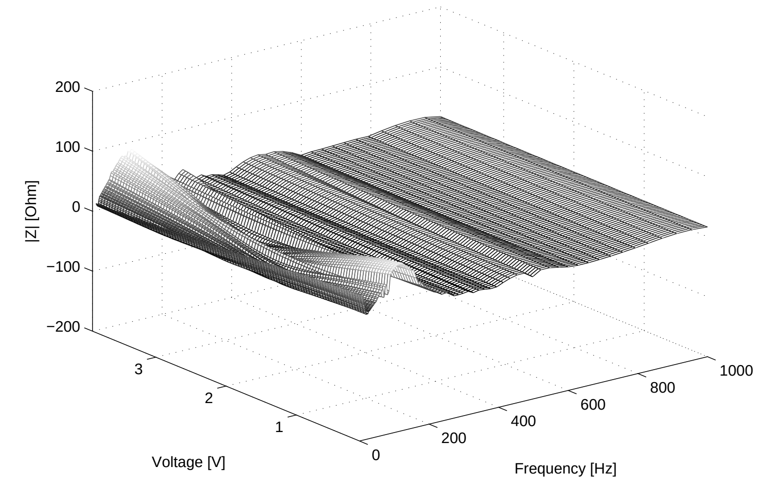

Fig. 5. Three-dimensional representation of the difference between the experimental impedance and the theoretical impedance ; the theoretical impedance is based on the Thiele and Small model with constant parameters (voltage: 0 V;4 V)(frequency: 0 Hz;1000 Hz)($|Z|$: -200Ω;+200Ω)

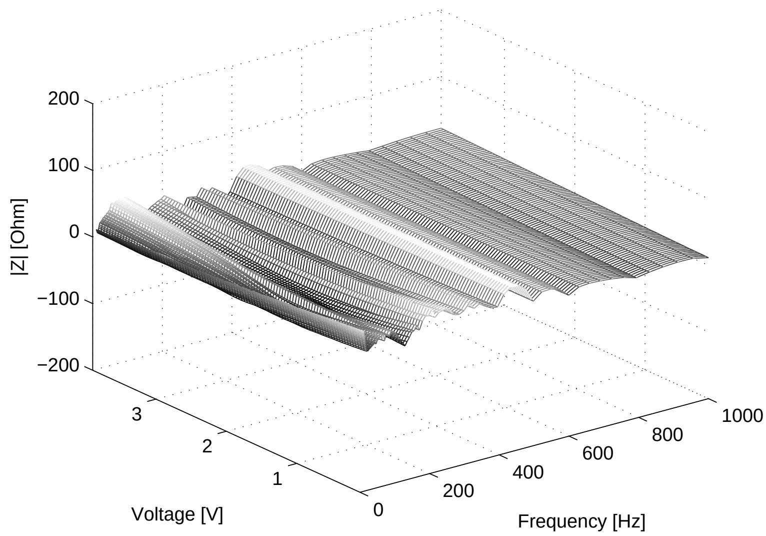

Fig. 6. Three-dimensional representation of the difference between the experimental impedance and the theoretical impedance ; the theoretical impedance is based on the Thiele and Small model with variable parameters (voltage: 0 V;4 V)(frequency: 0 Hz;1000 Hz)($|Z|$: -200Ω;+200Ω)

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

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

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

3.3 *Obtaining the nonlinear differential equation of the electrodynamic microphone*

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

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

By using (8) and 1, we deduct :

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

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

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

with

$$a = \frac{M_{ms} L_e}{Bl} \tag{11}$$

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

$$c = \frac{(R_e R_{ms} + Bl^2 + k L_e)}{Bl} \tag{13}$$

$$d = \frac{k R_e}{Bl} \tag{14}$$

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

$$U = a(jw)^3 X + b(jw)^2 X + c(jw) X + dX \tag{15}$$

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

$$U = X \left(A(jw)^3 + B(jw)^2 + C(jw) + D \right) \tag{16}$$

Thus

$$U = \chi X \tag{17}$$

where $\chi = (A(jw)^3 + B(jw)^2 + C(jw) + D)$. In the previous section, we studied the fact that the five Small signal parameters depended on input voltage. We deduct that these parameters can also be written as a function of the voice coil position X. Therefore, the parameters a, b, c and d in 10 become $a(x)$, $b(x)$, $c(x)$ and $d(x)$ in the nonlinear differential equation of the electrodynamic microphone. It is to be noted that solving this nonlinear differential equation is rather difficult because the denominator is not constant. It can be noted that this equation must be solved numerically in order to determine the distortions created by an electrodynamic microphone. In fact, the distortions created by a nonlinear system can be determined either analytically by using for example a Taylor series expansion or numerically. In the case of the electrodynamic microphone, we have chosen to solve numerically its nonlinear differential equation with Mathematica. This allows us to confirm the experimental displacement spectrum measured with the laser Doppler velocimeter.

3.4 Comparison between the theoretical displacement spectrum and the experimental displacement spectrum

A way of obtaining the theoretical displacement spectrum is to solve numerically the nonlinear differential equation of the electrodynamic microphone. This can be done for example in the time-domain by assuming that the electrodynamic microphone generates only harmonics that are multiple of the fundamental harmonic (w, 2w, 3w). This is a simplifying assumption because input voltage owns in reality many terms so that other typical nonlinear phenomena appear (intermodulations). In short, we assume the solution of the nonlinear differential equation of the electrodynamic microphone to be as the following form:

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

The parameters a_1, a_2, a_3, a_4, a_5 and a_6 are determined numerically and are 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)

3.5 Experimental and theoretical displacement spectrums

This section presents a comparison between the experimental displacement spectrum of the electrodynamic microphone which has been obtained by using a laser Doppler velocimeter and the theoretical displacement spectrum obtained by using the solution given in Eq. (18). The experimental and theoretical values are given in table 3. Moreover, the results obtained are plotted in Fig. 7. The theoretical displacement spectrum is consistent with the experimental displacement spectrum. Consequently, we deduct that the experimental way of characterizing the electrodynamic microphone with its electrical impedance allows us to precisely estimate the nonlinear variations of the Small 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

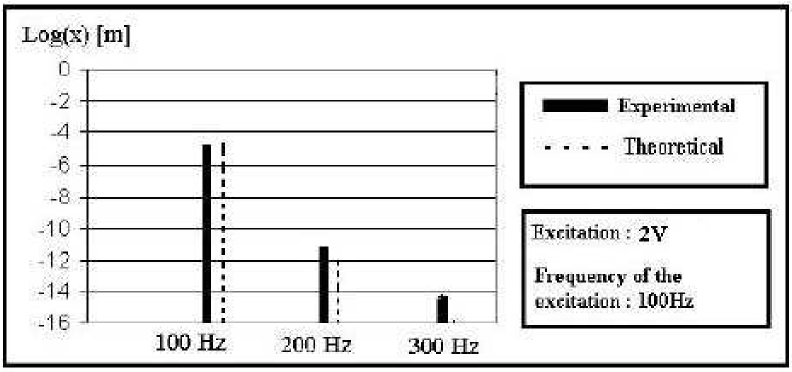

Fig. 7. Experimental and Theoretical spectrums of the electrodynamic microphone

4 Conclusion

In this paper, we studied the nonlinear effects of electrodynamic microphones that occur when they are used as acoustical sources. This functioning occurs in reciprocal calibration techniques. An experimental method, based on a very precise electrical impedance measurement allows us to put forward a measurement algorithm which is used to acquire as many points as possible. This measurement algorithm has been put forward in the case of the nonlinear study of electrodynamic loudspeakers. Taking into account the variations of the Small signal parameters with the input voltage allows us to improve significantly the model of the electrodynamic microphone. The variations of the Small signal parameters generate any distortions. These distortions can be predicted by solving numerically the nonlinear differential equation of the electrodynamic microphone. The comparison between the theoretical displacement spectrum and the experimental displacement spectrum shows a very good agreement at low frequencies.

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