DOI: 10.61782/fa.2023.0604

forumacusticum 2023

A PHYSICAL MODEL FOR THE ELECTROMAGNETIC LOUDSPEAKER USED IN EARLY ONDES MARTENOT *DIFFUSEURS*

Marc Wijnand[12*] **Henri Boutin**[1] **Marguerite Jossic**[2] **Thierry Maniguet**[2]
[1] S3AM team, STMS Lab UMR9912
(Ircam – CNRS – Sorbonne Université – Ministère de la Culture), Paris
[2] Équipe Conservation Recherche, Musée de la Musique,
Cité de la Musique - Philharmonie de Paris
& Centre de Recherche sur la Conservation, CNRS-USR3224,
Muséum National d'Histoire Naturelle, Ministère de la Culture, Paris

ABSTRACT

The ondes Martenot is an electric musical instrument that was presented for the first time in Paris in 1928. An electrical waveform is generated by a heterodyne oscillator whose fundamental frequency is controlled by modifying the oscillator capacitance/inductance using a ribbon/keyboard. A drawer enables the performer to filter the wave and to specify the volume and articulation. The resulting wave is fed to one or multiple *diffuseurs*, that convert it into soundwaves.

The first *diffuseurs* used a so-called electromagnetic (or moving-iron) loudspeaker, that was combined around 1937 with an electrodynamic (or moving-coil) loudspeaker, which is the standard technology today.

The behaviour of a less known electromagnetic loudspeaker from 1937 is studied with the longer term goal to preserve the sound heritage of an instrument whose conservation state does not allow for musical practice. The loudspeaker consists of a permanent magnet and two electromagnets whose combined flux lets a metal reed vibrate. A rod connects the moving reed to the apex of a paper cone, that generates the resulting soundwave.

In the current paper, a minimal physical model for this electromagnetic loudspeaker is derived. It is shown that its operating principle is inherently nonlinear, as opposed to the linear Thiele & Small model for electrodynamic loudspeakers. Furthermore, a first experimental measurement on a heritage *diffuseur* enables to quantify the nonlinearities presented by the electromagnetic loudspeaker.

****Corresponding author***: *marc.wijnand@sorbonne-universite.fr, postdoctoral researcher of the Collegium Musicæ of Sorbonne Université.*

Keywords: *electromagnetic loudspeaker, musical acoustics, electric musical instrument, heritage preservation.*

1. INTRODUCTION

1.1 Ondes Martenot

The ondes Martenot is an early electric musical instrument, invented by Maurice Martenot (1898-1980) [1, 2]. The instrument is in constant evolution and categorized in 7 models.

The first model is presented in 1928 during a concert at the Opéra de Paris, played by *jeu à distance*: the standing musician moves a string to control pitch.

During the *Exposition Universelle* in Paris in 1937 [3, 4], the fifth model is presented (Fig. 1). An electric waveform is generated from a fixed and variable high frequency oscillator by a heterodyne circuit with vacuum tubes. The fundamental frequency of the played note is controlled by the right hand of the musician by modifying the oscillator capacitance/inductance using a ribbon/keyboard [2]. The drawer (Fig. 2) is operated by the left hand. An intensity key is depressed to specify volume and articulation. Several switches enable to modify the timbre by filtering. The resulting electric wave is sent to one or multiple *diffuseurs* activated by four switches.

1.2 *Diffuseurs*

The electric wave generated by the instrument is converted into a sound wave by use of one or several *diffuseurs*.

1.2.1 Chronology

One can discern following types of *diffuseurs*.

1. The earliest versions of the instrument most likely used commercially available electromagnetic loudspeakers (that will be discussed below), such as the example seen in Fig. 3(a).

Figure 1: Ondes 169 (E.991.8.4) from 1937 and its principal components [Photo © Claude Germain, Philharmonie de Paris]

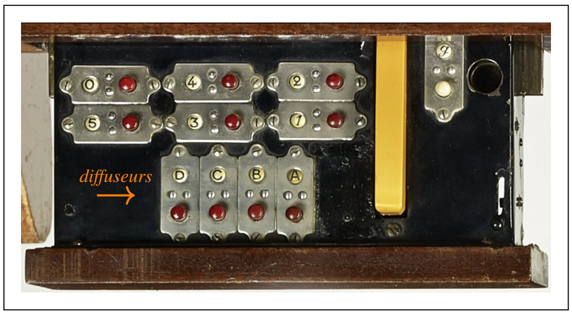
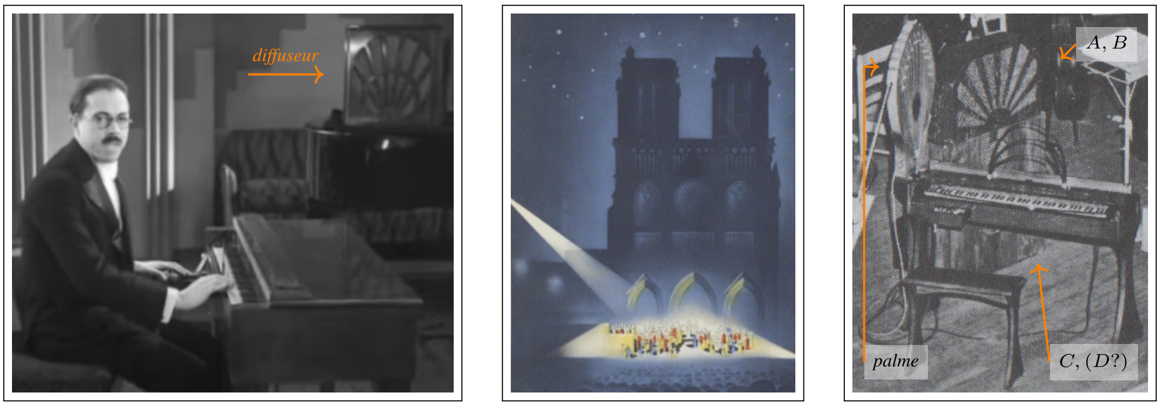


Figure 2: Drawer of ondes 169 (E.991.8.4): selection of *diffuseurs* A, B, C, D [Photo © Claude Germain, Philharmonie de Paris]

2. The 5th ondes Martenot model (1937) used up to 4 *diffuseurs*, denoted A, B, C, D as seen on the drawer (Fig. 2). On Fig. 3(c), one sees the *diffuseur* AB containing an electrodynamic loudspeaker (A) and an electromagnetic loudspeaker (B), that will be studied below. An instance of the *diffuseur* C preserved at the Musée de la Musique contains an electrodynamic loudspeaker with an amplifier, and a second amplifier for the *diffuseur* D that was probably an electrodynamic loudspeaker as well.

This ondes model has been used in several outdoor musical performances, for instance during the *Exposition Universelle* in Paris in 1937 and the show *Le Vray Mistère de la Passion* in front of the Notre-Dame cathedral (Fig. 3(b)), as described in [7]. The author witnesses the power and range of the sound that could be heard at very large distance, which corresponds to the aforementioned presence of power amplifiers.



(a) 1934, chamber music by Maurice Martenot demonstrating an earlier ondes version [5] [Video © British Pathé]

(b) 1937, outdoor concerts [6, 7] [Photo © `gallica.bnf.fr` / Bibliothèque Nationale de France]

(c) 1949, concerts in Boston [Photo © J. Walter Green, Collection Ginette Martenot-Lazard, reproduced from [1]]

Figure 3: References of early *diffuseurs*

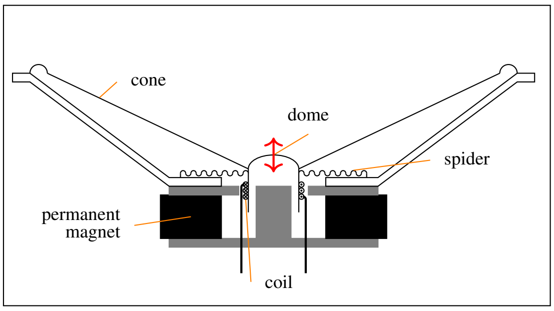
3. Later, next to a *diffuseur principal* (electrodynamic loudspeaker with standard cone), Martenot has designed several *diffuseurs* that are meant to influence the timbre and reverberation of the produced sound [8]: *métallique* (1944-1945 [9, p. 116], patented in 1947, a gong excited by a motor), *palme* (1949-1950, an electromagnet driving 12 metal strings attached to a soundboard [10], shown in Fig. 3(c)), *résonance/réverbéré* (1970s, used with the transistored 7th ondes model, metal springs excited by a motor). These *diffuseurs* are indicated by D^1, D^2, D^3, D^4 in musical scores and are still used by *ondists* today.

1.2.2 Contribution

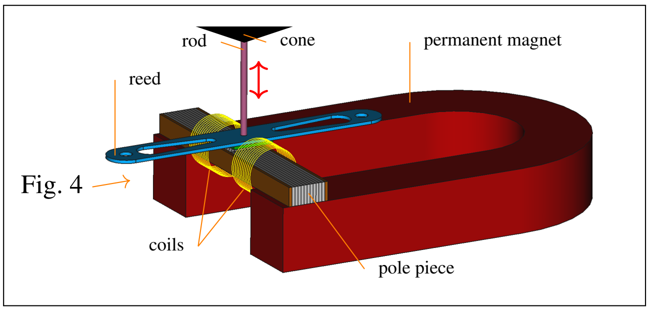
The few electromagnetic loudspeakers that are conserved do not allow for occasional or regular musical practices and are not well known. The goal of the present project is to study their behaviour using physical modelling and identification by experimental measurements.

In the longer term, the obtained results could be used to reconstruct the sound [11] by numerical sound synthesis [12], constructing a facsimile, or active control of contemporary loudspeakers, in order to preserve the sound heritage of this musical instrument.

(a) *Diffuseur* AB of ondes 132 (E.982.9.1) from 1930-1934



(b) *Diffuseur* A: electrodynamic loudspeaker



(c) *Diffuseur* B: electromagnetic loudspeaker

Figure 3: *Diffuseur* AB

2. THE *DIFFUSEUR AB*

Two *diffuseurs* AB are conserved at the Musée de la Musique de la Philharmonie de Paris: one corresponding to ondes 132 dated from 1930-1934 (E.982.9.1, shown in Fig. 3(a)) and one corresponding to ondes 169 dated from 1937 (E.991.8.4).

2.1 *Diffuseur A*: electrodynamic loudspeaker

The structure of the electrodynamic (or moving coil/conductor) loudspeaker is shown in Fig. 3(b). An oscillating current $i(t)$ flows in a coil that is located inside a radial magnetic field. Therefore, a Laplace force $F(t)$ is created that is proportional to the current:

$$F(t) = B\ell i(t), \tag{1}$$

with ℓ the length of the coil inside the magnetic field of strength B. This force is applied to the moving element that lets the cone vibrate, the latter being modeled as a linear lumped mass(m)-spring(k)-damper(c) system of transverse position $y(t)$:

$$F(t) = m\ddot{y}(t) + c\dot{y}(t) + ky(t).$$

The voltage at the loudspeaker terminals depends on the circuit's resistance R, inductance L, and counter-electromotive force depending on the cone velocity $\dot{y}$:

$$v(t) = Ri(t) + L\frac{\mathrm{d}i(t)}{\mathrm{d}t} - B\ell\dot{y}(t).$$

This elementary linear model is known as the Thiele & Small model [13, 14]. It constitutes a time-invariant lumped-parameter model that is valid for excitations that are low-frequency, low-amplitude and short. Secondary nonlinearities [15, 16], such as space variation of the force factor $B\ell$ at great displacements, are not taken into account.

2.2 *Diffuseur B*: electromagnetic loudspeaker

The structure of the electromagnetic (or moving iron/armature) loudspeaker is represented in Fig. 3(c). This older loudspeaker type has evolved from headphones with a vibrating ferromagnetic plate, that has been replaced by an acoustically more efficient paper cone driven by a ferromagnetic reed. There exist a variety of motor layouts differing in the form of reed and number and orientation of permanent magnet(s) and coil(s); and thus in size and efficiency [17, 18].

A magnetic flux path is created that passes through the reed via a (varying) air gap. The flux $\Phi(t)$ in the air gap gives rise to a force

$$F(t) = \frac{\Phi^2(t)}{2\mu_0 A_\mathrm{a}} \tag{2}$$

on the reed trying to close the air gap, according to [18, Eq. (7.1)]- [19, Eq. (4.47)], with μ_0 the vacuum magnetic permeability and A_a the surface of the air gap.

The total flux $\Phi(t)$ is composed of a contribution Φ_0 by the permanent magnet(s), and a time-varying contribution $\Phi_1(t)$ by the coil(s). Let [1] $\Phi_1(t) = \Phi_\mathrm{c}\cos\omega t$. As discussed in [17, pp. 12-13], this corresponds to a force

$$\begin{aligned} F(t) &= \frac{(\Phi_0 + \Phi_\mathrm{c}\cos\omega t)^2}{2\mu_0 A_\mathrm{a}} \\ &= \frac{1}{2\mu_0 A_\mathrm{a}}\left(\underbrace{\Phi_0^2 + \frac{\Phi_\mathrm{c}^2}{2}}_{\text{DC}} + \underbrace{2\Phi_0\Phi_\mathrm{c}\cos\omega t}_{\text{fundamental}} + \underbrace{\frac{\Phi_\mathrm{c}^2}{2}\cos 2\omega t}_{\text{octave}}\right). \end{aligned} \tag{3}$$

The DC term determines the resting position of the reed. The amplitude of the useful force component with fundamental pulsation ω depends on both the coil flux and the flux of the permanent magnet. The last term represents a nonlinear distortion in the form of a force with double pulsation 2ω.

As mentioned in [20] as well, if there were no permanent magnet ($\Phi_0 = 0$), there would only be a force component at the double frequency: the coil would attract the reed twice per period. Furthermore, it is not feasible to reduce Φ_c in order to reduce the octave harmonic, as this would require a larger Φ_0 to compensate for the loss of sound volume at the fundamental frequency, which would lead to ferromagnetic saturation.

The force (2) applied to the reed is transmitted by the rod to the apex of the cone, that can again be modeled as a mass-spring-damper system.

It turns out that the electromagnetic loudspeaker type is inherently nonlinear because the generated force depends quadratically on the current [2], instead of the linear relation (1) for the electrodynamic loudspeaker, even without taking into account secondary nonlinear phenomena such as eddy currents and magnetic saturation. A second drawback of this type of loudspeaker is its smaller bandwidth as compared to the electrodynamic loudspeaker [21].

Until 1930, the electromagnetic loudspeaker was still the most used technology. As mentioned in [22], both types of loudspeakers coexisted in the 1930s and could even be used simultaneously if wanted. Later, the electrodynamic loudspeaker would become the standard type because of its better characteristics and advancing technology. Martenot's *diffuseur AB* (1937) corresponds to this evolution. It is possible that he used only electrodynamic loudspeakers for the amplified *diffuseurs CD* because the nonlinear character of electromagnetic loudspeakers would be more prominent at higher excitation levels [17], and to have a wider bandwidth.

The current study focuses further on the mentioned *diffuseur B* for which a physical model is established in Section 3, followed by first experimental measurements in Section 4.

[1] A more explicit formulation of the force $F(t)$ for the considered electromagnetic loudspeaker layout will be given by (5), that shows its dependence on excitation current $i(t)$ and air gap size $l_\mathrm{a}(t)$.

[2] Although some more advanced layouts allow to partially remove the quadratic dependence [17].

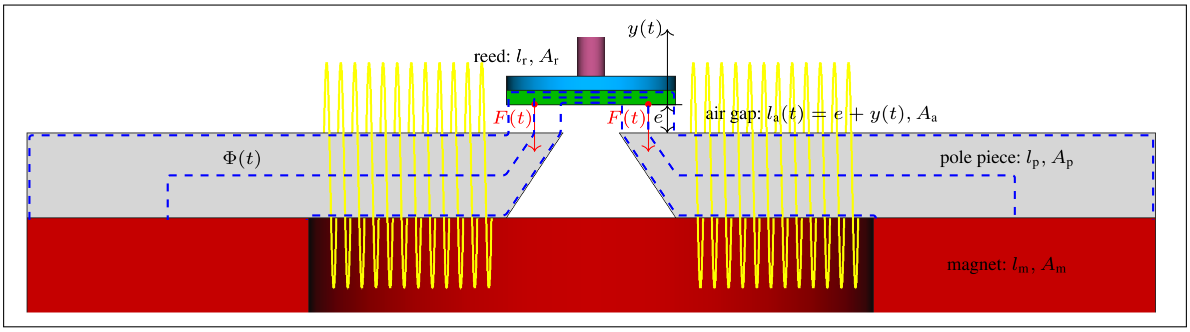


Figure 4: Idealized flux path through pole pieces, air gaps and reed, at rest position ($y = 0$), as seen in the direction indicated in Fig. 3(c). The figure is not to scale; especially, the transverse distance e is exaggerated for clarity.

3. PHYSICAL MODEL

The elementary physical model for the moving iron loudspeaker introduced in Subsec. 2.2 is further developed here. This approach based on the magnetic circuit and air gap force was applied to an alternative electromagnetic motor layout, the balanced-armature motor, in [18, Ch. 7] (applied to telephony and relays) and [23] (applied to hearing aid receivers).

3.1 Magnetic domain

Following assumptions are made.

- Secondary nonlinear effects such as eddy currents, ferromagnetic saturation and hysteresis are neglected. All ferromagnetic materials behave linearly.
- There is no leakage flux: the magnetic flux is concentrated in the ferromagnetic materials and the air gaps.
- The reluctance of ferromagnetic materials is neglected compared to the reluctance of the air gap.

For that case, the idealized flux path between the poles of the horseshoe magnet is shown in Fig. 4. The pole pieces are laminated to reduce eddy current losses. They are interrupted beneath the reed, except for a first and last layer for structural purposes. Because of this large horizontal air gap, the flux is directed through the reed across a very small transverse air gap[3].

The corresponding magnetic circuit is schematized in Fig. 5.

It contains following magnetomotive forces: a constant contribution $\mathcal{F}_m$ by the permanent magnet and a time-varying contribution

$$\mathcal{F}_c(t) = \frac{N}{2} i(t)$$

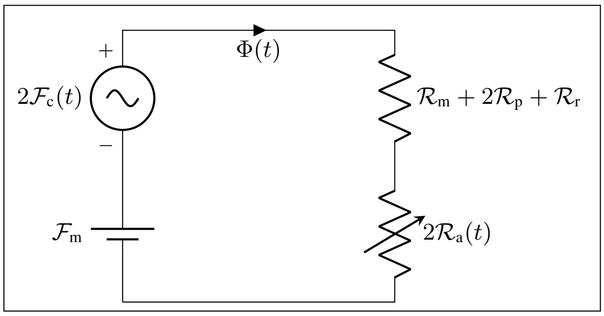


Figure 5: Magnetic circuit model

for each of the coils, each having $N/2$ turns.

To each part $i \in \{$m(agnet), p(ole piece), a(ir gap), r(eed)$\}$ of the magnetic circuit corresponds a magnetic reluctance

$$\mathcal{R}_i = \frac{l_i}{\mu_i \mu_0 A_i}$$

depending on equivalent length l_i and surface A_i, and relative magnetic permeability μ_i w.r.t. the vacuum magnetic permeability μ_0.

The air gap has a variable length $l_a(t) = e + y(t)$ as function of the transverse position $y(t)$ of the reed. Its reluctance is

$$\mathcal{R}_a(t) = \frac{e + y(t)}{\mu_0 A_a}.$$

It is assumed that the remaining magnetic reluctance

$$\mathcal{R}_m + 2\mathcal{R}_p + \mathcal{R}_r = \frac{l_m}{\mu_m \mu_0 A_m} + 2\frac{l_p}{\mu_p \mu_0 A_p} + \frac{l_r}{\mu_r \mu_0 A_r}$$

is much smaller than $\mathcal{R}_a$ and can be neglected. The total flux $\Phi(t)$ can then be calculated by Rowland-Hopkinson's law as

$$\Phi(t) = \frac{\mathcal{F}_{tot}(t)}{\mathcal{R}_{tot}(t)} = \frac{\mathcal{F}_m + 2\mathcal{F}_c(t)}{2\mathcal{R}_a(t)} = \frac{\mu_0 A_a}{2} \frac{\mathcal{F}_m + Ni(t)}{e + y(t)}. \quad (4)$$

[3] The air gap in electromagnetic loudspeakers has to be perfectly flat [17] and is very small: typical values in the range 1/10mm-1/50mm [17] are mentioned. Furthermore, a mechanical tuning system enables to modify this distance in order to control the sensitivity of the speaker as function of the maximal volume of the sound that is being played [17]. When the excursion is too big, the reed will touch the pole pieces, which is not wanted except for the case of telegraph transmission [24].

Substituting (4) in (2), one obtains the magnitude

$$F(t) = \frac{\mu_0 A_\mathrm{a}}{8} \frac{\mathcal{F}_\mathrm{m}^2 + 2N\mathcal{F}_\mathrm{m} i(t) + N^2 i^2(t)}{(e + y(t))^2} \tag{5}$$

for the force that is generated in each of the two air gaps (Fig. 4).

3.2 Mechanical domain

In both air gaps, the force (5) is applied to the middle of the reed, that is clamped at its both extremities (not shown in Fig. Fig. 3(c)) and that is coupled to the cone by a rod. This constitutes a stiff mechanical system that executes small transverse displacements. The reed is dimensioned so as to have eigenfrequencies outside the hearing range, with some material removed to lower the area moment of inertia [17].

Here, a lumped modeling approach is followed, where the combined dynamics of reed and cone are modeled as a linear mass(m)-spring(k)-damper(c) system, excited by an air gap force in the two air gaps (from Eq. 5):

$$2F(t) = m\ddot{y}(t) + c\dot{y}(t) + ky(t). \tag{6}$$

3.3 Electrical domain

The voltage $v(t)$ at the motor terminals depends on the current $i(t)$ and magnetic flux $\Phi(t)$ (that is modified with varying current $i(t)$ and reed position $y(t)$) according to [23]

$$v(t) = Ri(t) + N \underbrace{\frac{\partial \Phi(i(t), y(t))}{\partial i(t)}}_{\triangleq L(i(t), y(t))} \frac{\mathrm{d}i(t)}{\mathrm{d}t} + N \underbrace{\frac{\partial \Phi(i(t), y(t))}{\partial y(t)}}_{\triangleq T(i(t), y(t))} \frac{\mathrm{d}y(t)}{\mathrm{d}t}.$$

For the studied motor, one obtains

$$v(t) = Ri(t) + \frac{\mu_0 A_a}{2} \frac{N^2}{e + y(t)} \frac{\mathrm{d}i(t)}{\mathrm{d}t} - \frac{\mu_0 A_a N}{2} \frac{\mathcal{F}_m + Ni(t)}{(e + y(t))^2} \frac{\mathrm{d}y(t)}{\mathrm{d}t}. \tag{7}$$

The corresponding electric circuit is schematized in Fig. 6.

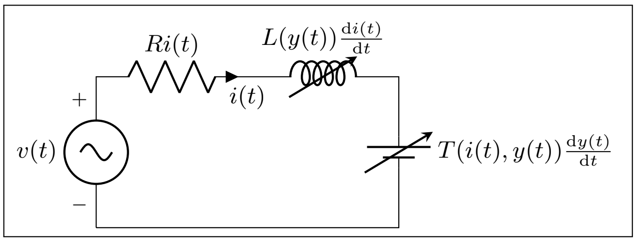


Figure 6: Electric circuit model

4. MEASUREMENTS

The experimental setup for measurements of the *diffuseur B* of ondes 169 is schematized in Fig. 7. A voltage signal is provided by a function generator[4] fed to an amplifier[5] with gain $\nu = 21.25$. The voltage $v(t)/\nu$ before amplification is measured, as well as the current $i(t)$ (sensor[6]), produced sound pressure $p(t)$ at a chosen distance (microphone[7]), and acceleration $\ddot{y}(t)$ (accelerometer[8] at the top of the connecting rod in the center of the cone).

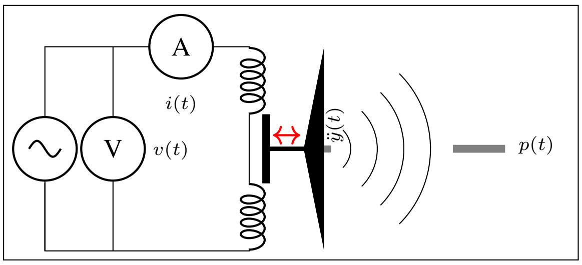


Figure 7: Scheme of the experimental setup with measurement of 4 signals

4.1 Preliminary identification

Following physical quantities present in the model (6)-(7) can be obtained immediately. The DC resistance[9] R of the two coils in series amounts to $606\,\Omega$ (ohmmeter). The air gap length at rest is $e \approx 0.46\,\mathrm{mm}$ and the air gap surface $A_\mathrm{a} \approx 44\,\mathrm{mm}^2$ (estimated on photos due to difficult access).

4.2 Spectral enrichment

The loudspeaker is driven by a sine voltage $v(t) = V_0 \sin(2\pi f_0 t)$ with amplitude $V_0 \in \{10.63, 21.25, 31.88, 42.5, 63.75, 85, 106.25\}\mathrm{V}$ and frequency $f_0 \in \{50, 100, 500, 1000\}\mathrm{Hz}$.

The corresponding acceleration signals $\ddot{y}(t)$ (e.g. Fig. 8) are registered. Their frequency spectra obtained by Welch's method are shown in Fig. 9

At each frequency f_0, one observes the gradual appearance of harmonics as the excitation amplitude V_0 is increased. Moreover, the odd harmonics (at $(2n+1)f_0$, $n \in \mathbb{N}$) are more present than the even ones (at $2nf_0$).

Figure 10 shows the evolution of the total harmonic distortion (THD) that is calculated as $\mathrm{THD} \approx \sqrt{\sum_{n=2}^{10} A_n^2}/A_1$, where A_n is the amplitude of the peak at $f = nf_0$ in the spectrum.

[4] TTi TG2000 with nominal THD $< 0.3\%$
[5] Thomann PM40C with nominal THD plus noise of 0.03%
[6] Newtons4th Ltd HF003; [7] Schoeps MK 4; [8] Dytran 3225F1
[9] Typical values for used coils are a DC resistance of $500 - 1500\,\Omega$, and an inductance of $2 - 3\,\mathrm{H}$ [17].

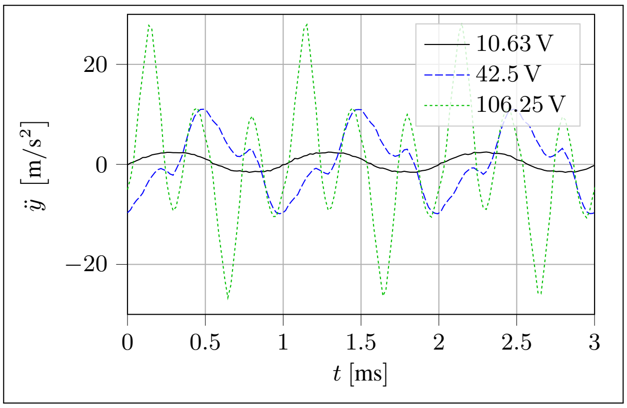


Figure 8: Measured acceleration signals $\ddot{y}(t)$ for excitation at $f_0 = 1000$ Hz as function of amplitude V_0

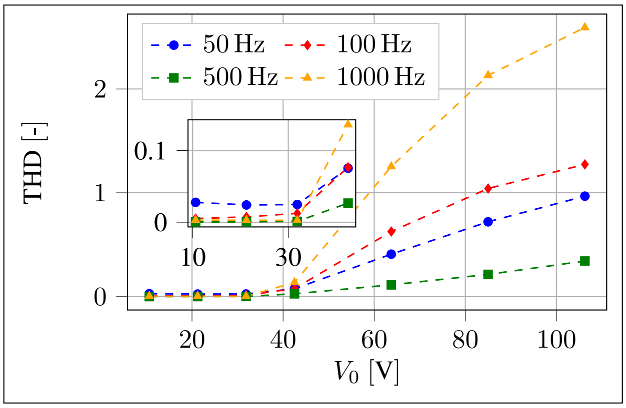
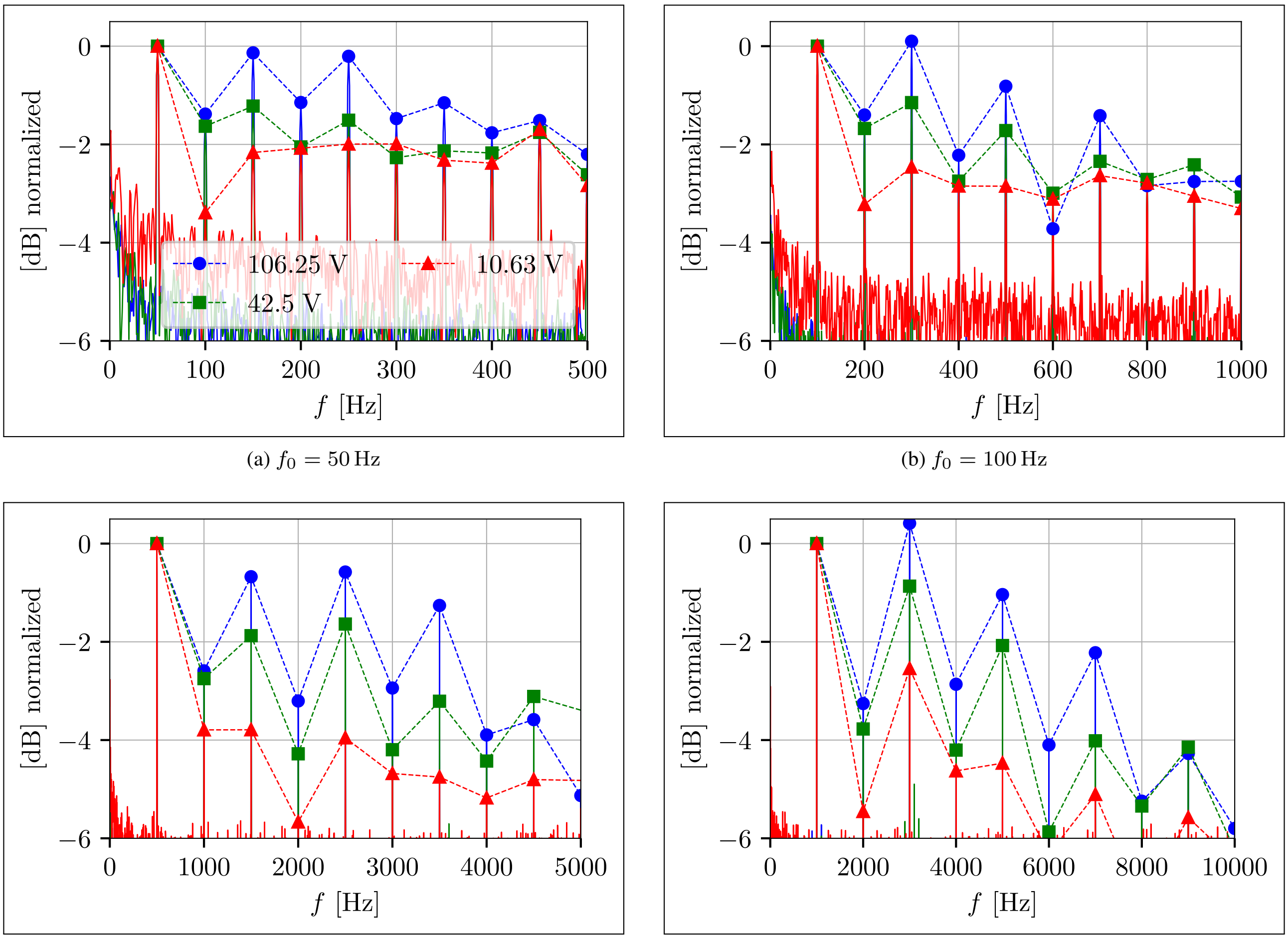


Figure 10: Evolution of THD of $\ddot{y}(t)$ as function of sine voltage excitation amplitude V_0 and frequency f_0



(a) $f_0 = 50$ Hz

(b) $f_0 = 100$ Hz

(c) $f_0 = 500$ Hz

(d) $f_0 = 1000$ Hz

Figure 9: Spectra of measured acceleration signals $\ddot{y}(t)$ as function of excitation frequency f_0 and amplitude V_0, calculated by Welch's method. The vertical axis is expressed in dB $\left({}^{10}\log(\cdot)\right)$ and the amplitude at f_0 is normalized to be 0 dB. Symbols indicate the amplitudes of the contributions at frequencies nf_0 for clarity.

As mentioned in [18, Ch. 7], the expression for the air gap force (3) does not allow to quantify the relative magnitudes at the fundamental and octave frequencies in the acceleration or sound signal, as mechanical impedance and radiation loading (including resonances) will modify their amplitudes.

5. CONCLUSION AND PERSPECTIVES

A minimal physical model was developed for an electromagnetic loudspeaker present in a *diffuseur* B that was paired with an ondes Martenot from 1937. It is shown that its operating principle is inherently nonlinear due to the air gap force.

A first experimental measurement on a heritage *diffuseur* enables to quantify the nonlinearities presented by the electromagnetic loudspeaker.

In future work, more detailed measurements with the presented test setup could be used to estimate all the physical parameters of the presented nonlinear minimal model. Furthermore, the model could be refined taking into account secondary nonlinearities.

6. ACKNOWLEDGMENTS

The authors thank ondes Martenot player Thomas Bloch and researcher Laurent Coolen at Sorbonne Université for useful discussions, Luise Allendorf-Hoefer at the Deutsches Museum in Munich for pointing out reference [17], and Francesca di Ludovico at the Università degli Studi di Urbino "Carlo Bo" for granting access to reference [7].

7. REFERENCES

[1] J. Laurendeau, *Maurice Martenot, luthier de l'électronique*. Louise Courteau Ed. Canada / Dervy-Livres France, 1990.

[2] T. Courrier, "Onde Martenot N°15/169, Analyse de fonctionnement," *Unpublished documents, Musée de la Musique de Paris*, 2012.

[3] N. Simeone, "Music at the 1937 Paris Exposition: The Science of Enchantment," *The Musical Times*, vol. 143, no. 1878, pp. 9–17, 2002.

[4] P. Asimov, "Une invention "essentiellement française": seeing and hearing the Ondes Martenot in 1937," *Musique, Images, Instruments: Revue française d'organologie et d'iconographie musicale*, vol. 17, pp. 107–126, 2018.

[5] "Music From The Ether (video)," British Pathé, 1934.

[6] "Le Vray Mistère de la Passion de Arnoul Gréban, Parvis Notre-Dame, 30/7/37 (recueil)," Bibliothèque Nationale de France.

[7] B. Disertori, "Le onde Martenot: lo strumento nuovo d'una nuova èra," *Rivista Musicale Italiana*, vol. 43, pp. 383–392, 1939.

[8] M. Martenot, "Sons physique - sons musicaux (Conférence faite à Gravesano, 12/8/54)," *Bulletin du GAM n°60*, 1972.

[9] J. Laurendeau, *Maurice Martenot, luthier de l'électronique*. Beauchesne, 2017.

[10] E. Leipp, "Les Ondes Martenot, un archétype," *Bulletin du GAM n°60*, 1972.

[11] D. Madden, "Advocating sonic restoration: Les Ondes Martenot in practice," *Wi: Journal of Mobile Culture*, vol. 7, no. 1, pp. 1–28, 2013.

[12] J. Najnudel, T. Hélie, D. Roze, and H. Boutin, "Simulation of an Ondes Martenot Circuit," *IEEE/ACM Transactions on Audio, Speech, and Language Processing*, vol. 28, pp. 2651–2660, 2020.

[13] N. Thiele, "Loudspeakers in vented boxes: Part 1," *Journal of the Audio Engineering Society*, vol. 19, no. 5, pp. 382–392, 1971.

[14] R. H. Small, "Closed-box loudspeaker systems-part 1: analysis," *Journal of the Audio Engineering Society*, vol. 20, no. 10, pp. 798–808, 1972.

[15] W. Klippel, "Loudspeaker nonlinearities–causes, parameters, symptoms," in *Audio Engineering Society Convention 119*, Audio Engineering Society, 2005.

[16] A. Falaize and T. Hélie, "Passive modelling of the electrodynamic loudspeaker: from the Thiele–Small model to nonlinear port-Hamiltonian systems," *Acta Acustica*, vol. 4, no. 1, p. 1, 2020.

[17] E. Popp, *Konstruktion und Bau elektromagnetischer Lautsprecher-Antriebssysteme*. Die Radio-Reihe, R. C. Schmidt, Berlin, 1929.

[18] F. V. Hunt, *ELECTROACOUSTICS – The Analysis of Transduction, and Its Historical Background*. Harvard University Press, 1954.

[19] P. Campbell, *Permanent magnet materials and their application*. Cambridge University Press, 1994.

[20] P. Hémardinquer, "Les haut-parleurs d'amateurs," *La Nature*, no. 2841, pp. 241–254, 15 septembre 1930.

[21] C. Vinogradow, "Le récepteur de T. S. F. ne déforme plus la musique," *La Science et la Vie*, no. 189, pp. 243–251, mars 1933.

[22] G. Mousseron, "Conseils aux sans-filistes," *La Science et la Vie*, no. 230, pp. 166–168, août 1936.

[23] J. Jensen, F. T. Agerkvist, and J. M. Harte, "Nonlinear time-domain modeling of balanced-armature receivers," *Journal of the Audio Engineering Society*, vol. 59, no. 3, pp. 91–101, 2011.

[24] J. Roussel, "LES APPAREILS HAUT-PARLEURS et leur application à la télégraphie et à la téléphonie sans fil," *La Nature*, no. 69-78, deuxième semestre 1922.