Intensity Key of the Ondes Martenot: An Early Mechanical Haptic Device

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Summary
While the Ondes Martenot is one of the oldest electronic musical instruments, it is still played today. It is known for making extremely expressive electronic sounds. A major advantage of the Ondes Martenot is that it enables players to control the temporal dynamics of notes in a particularly sensitive manner by pressing an "intensity key".
In this paper, the intensity key is characterized experimentally. Measurements were carried out on the force with which the musician presses on the key, the depression of the key, and the resulting sound. It is demonstrated that this key provides a broad dynamic range of 50 dB for each note over the entire range of the instrument. Moreover, the change in sound intensity of the notes depends only on the displacement of the intensity key and then on the force applied on it.
Mechanical parts of the intensity key were made for the musician to control finely and smoothly the variations of the sound produced by the instrument. A mechanical model is developed to explain experimental results. It appears that fine control is related to the mechanical behavior of the key: it acts as a well-chosen non-linear spring. It shows a linear relationship between the logarithm of the finger force on the key and the dB_{SPL} (sound pressure level) increase.

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1. Introduction

The Ondes Martenot, one of the oldest electronic musical instruments (first public audience in 1928 and still played today), showed that it was possible to make extremely expressive electronic sounds. A major advantage of the Ondes Martenot is that it enables players to control the intensity of music in a particularly sensitive manner, by pressing an "intensity key". First, the functioning of the instrument will be briefly described, before focusing on the intensity key. Second, experimental measurements will be carried out to link the musician's instrumental gestures (key's displacement, force with which it is pressed) with the intensity key's effects on the produced sound. Then a mechanical model will be proposed to describe this key's function. Finally, a discussion about the intensity key considered as an haptic device will be proposed.

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2. Ondes Martenot

2.1. Presentation

The Ondes Martenot is an electronic musical instrument invented by French Maurice Martenot in the 1920s. Despite the small number of instruments built (less than 300 [1, 2]), many works have been written for it (over 1500, according to [3]), by many composers (Olivier Messiaen, Maurice Ravel, Darius Milhaud, etc.). Usually this attraction is explained ([4]) by the expressiveness offered by the instrument. In particular, the intensity key "replaces the bow used with string instruments, the breath in wind and brass instruments. This infinitely sensitive key enables the sound to be shaped in the same way as a sculptor moulds his clay" ([5]).

2.2. Basic principles of functioning

Since its origins, the Ondes Martenot has evolved, and one generally distinguishes seven models ([5]), since the first model of 1928 until the advent of the model with transistors in the Seventies. Regardless of the model, the way the instrument is played remains the same: the right hand controls the pitch of the note

Figure 1: Playing the Ondes Martenot using the keyboard: right hand controls the pitch of the note while left hand adjusts the volume by pressing the intensity key.

and the left hand adjusts the volume (see Figure 1). Schematically (see Figure 2), the electrical signal is generated by a heterodyne oscillator whose frequency is determined by the right hand of the player via a keyboard very similar to a piano keyboard (see Figure 1) or a ribbon moved through a finger ring. The different tones are obtained by changing the shape of the oscillating signal (sine, square wave, triangular, etc.). Then, the performer's left hand finely controls the volume by pressing the intensity key. The modulated electrical signal is then amplified and converted into sound via the different speakers.

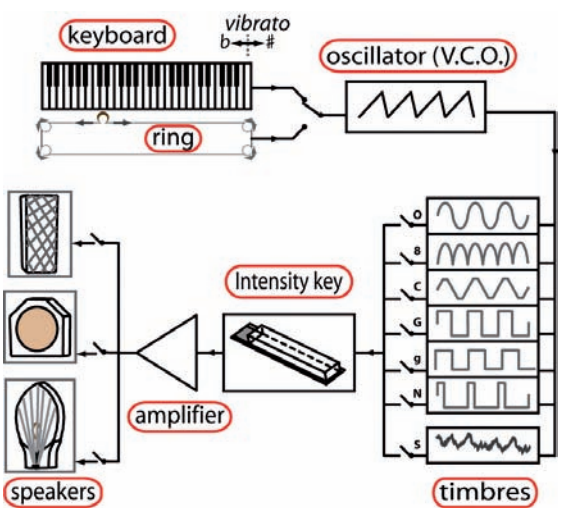

Figure 2: Functioning diagram of the Ondes Martenot (inspired by [5]).

3. Intensity key of the Ondes Martenot

This key functions as a variable rheostat. By pressing on a small powder bag (see Figure 3), containing a powder (a conductive/insulator mixture, made up with Graphite and Mica, [6]), the powder is compressed. It causes a sharp decrease in its electrical resistance and an increase in electrical current flow. It is the same working principle as the carbon microphone. Although this has been used for over hundred years ([7]), this effect has only been explained quite recently: it is related to micro-contacts between carbon beads ([8]) and a fast increase in the number of current paths (i.e. conductive beads in contact) inside the bag during compression ([9]).

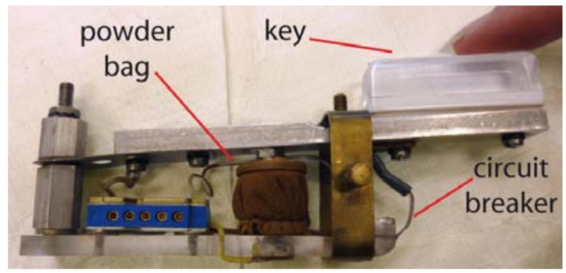

Figure 3: The intensity key removed from its drawer.

According to Olivier Messiaen (in the preface of [5]): "[...] it is the intensity key of the Ondes Martenot which I find to be the greatest invention. The intensity key, struck by one or several fingers of the left hand, gives at the same time the sound, its intensity, and the attack itself. Sound intensity ranges from an almost inaudible *pianissimo* to the most terrible and painful *fortissimo*, passing through all intermediate gradations. The possible attacks are more numerous than those of the piano, violin, flute, horn or organ. They range from an absolute *legato* to the driest *staccato*, going through *louré*, *piqué* and *pizzicato* to finish with ¨*percussion*¨ sounds".

4. Experimental setup

Measurements were carried out ([10, 11]) to characterize this intensity key. Measurements of the force with which the Ondist presses the key, as well as measurements of the depression of the key and of the resulting sound were carried out. All these measurements were performed simultaneously and in playing conditions.

4.1. Experimental protocol

The Ondes Martenot is a rare instrument. The number of instruments still in a playable state is estimated at less than eighty ([2]). All the measurements presented here were made on an instrument owned by the Paris Conservatoire (CNSMDP), a transistor model (the Ondes Martenot number 320).
To measure the displacement of the key, an inductive proximity sensor (ref. Contrinex, mod. DW-AD-509-M12-390) was used (precision ±0.1 mm) by sticking a

metal target at the rear end of the key. This inductive sensor generates a magnetic field that is attenuated by the metal target and its output depends on the degree of attenuation (and so the distance between the sensor's head and the target). Because there is no contact between the sensor and the key, it does not modify the mechanical properties of the key.

To measure the force, a F.S.R. pressure sensor was used (Force Sensing Resistor Interlink, mod. 402). Its electrical resistance varies according to the pressure of the finger on its sensitive part. Instead of using an epoxy dome ([12], [13]) for spreading the applied force through the effective sensing area (ø 14.7 mm), a small ring of white foam (see in Figure 4) is used in order to maintain a flat surface (to avoid disturbing the musician) and to ensure that the finger entirely covers the sensitive surface. Our calibrations (10 repeated calibration measurements with different normalized weights) show that this sensor has a ±15 % accuracy. Such accuracy is not unusual for an F.S.R. pressure sensor, as dependence on loading history is not compensated by signal conditioning (like in [14],[15]). This sensor is extremely thin (0.4 mm) and light (0.3 g) ; in comparison, the weight or thickness of the intensity key used are 30 g and 15 mm, and variations between different Ondes Martenot can exceed 10%.

Finally, a microphone (Brüel & Kjaer, type 4191) was used to measure the sound produced by the instrument through its speaker. It faced the speaker of the instrument, one meter away on the symmetry axis. The microphone was previously calibrated at 104 $\mathrm{dB_{SPL}}$(Sound Pressure Level) with a calibrated source.

All measured signals were simultaneously digitized by a digital acquisition board (ref. National Instrument NI 9234) with a sampling rate of 51.2 kHz.

To specify the force and displacement bandwidths used when pressing the key, a series of measurements were carried out. The entire dynamic range of the instrument was explored, for different fixed notes using a *crescendo* for each C of the range (C_1 to C_7). The *crescendo* duration was a few seconds. The chosen timbre (see Figure 2) for the instrument was the "timbre 'O' " which corresponds to a purely sinusoidal shape for the electrical signal. All experiments have been performed by the authors, who are not professional Ondists.

4.2. Results

This section provides results of measurements made with the experimental protocol described in Section 4.1. First, the effect of the intensity key on the amplitude of the electric signal after the bag is shown. Then, the link between this amplitude and the frequency of the signal is described, as well as the link between this amplitude and the key's displacement. Finally, the link between the key's displacement and the force with which it is pressed is studied.

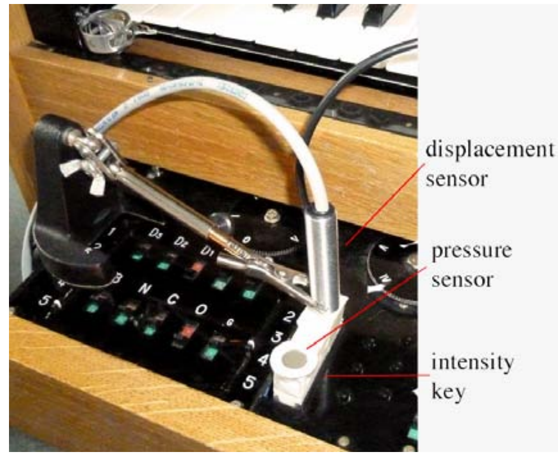

Figure 4: Intensity key instrumented with sensors.

4.2.1. The intensity key : an amplitude modulator

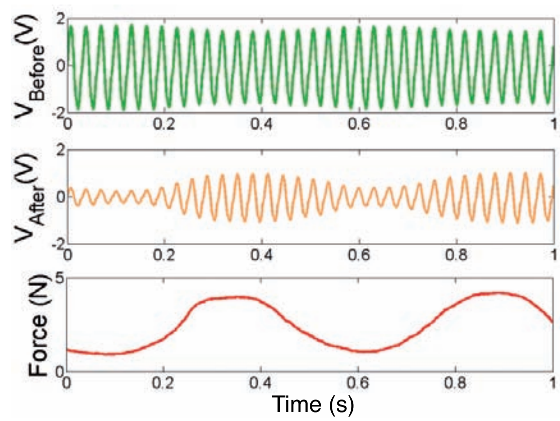

Figure 5: Measurements of the time signals of the electrical voltage before (Top) and after (Middle) the bag, and the force applied on the key (Bottom).

Figure 5 shows measurements of the time signals of the electric voltage *before* and *after* the powder bag under the key, and the force applied on the key when a C_1 (32 Hz) is played. These three signals have been recorded simultaneously for 1 second while pressing the key twice. When the key is not pressed, the amplitude of the electrical signal after the bag is null because of the circuit breaker (see Figure 3). When the finger presses on the key with a force of 4.2 N, the amplitude of the electrical signal *before the bag* decreases by 14 % (from 1.7 V to 1.47 V) compared to when it is pressed with a force of 1 N. However, the amplitude of the electrical signal *after the bag* increases by 453 % (from 0.22 V to 1 V). Thus, the intensity key achieves an amplitude modulation of the electric audio signal when pressing on the bag.

4.2.2. Amplitude VS Frequency

The powder contained in the bag may have capacitive effects. In order to measure these capacitive effects, a square signal is injected at the input of the bag removed from the key. At the output of the bag, this signal is measured in order to determine its cut-off frequencies. The cut-off frequency of the equivalent capacitor in parallel is $f_{c_1} = 40\,\mathrm{kHz}$, while the cut-off frequency of the equivalent capacitor in series is $f_{c_2} = 800\,\mathrm{kHz}$. Thus the bag has negligible capacitive effects in the audio bandwidth.

Consequently, the powder bag can be removed and replaced by resistors to study the effect of the signal frequency on its amplitude at constant resistance (in other words, *at a fixed position of the key*). Figure 6 shows the amplitude of the signal V_{bag} measured at the output of the resistances that replace the bag. These amplitudes have been measured on the complete bandwidth of the instrument (from 65 Hz to 4 kHz) using its ring to achieve a continuous *glissendo* (sweep).

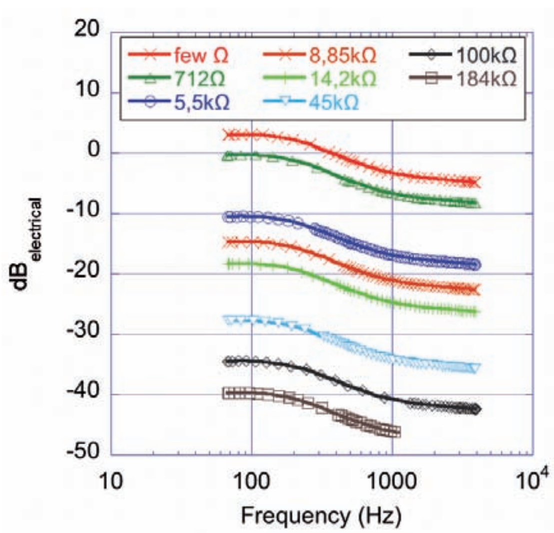

Figure 6: Variations of V_{bag} according to the frequency with different resistances: from top to bottom, resistance increases from few Ω to 184 kΩ.

The amplitude increases when the resistance decreases, as much as 43 dB when going from 184 kΩ to a few Ω (single electrical wire). Along a resistance line, the amplitude decreases as much as 8 dB when the frequency increases. Furthermore, all curves with different resistances have exactly the same shape.This means that the effect of the frequency on the amplitude does not depend on the resistance, thus on the intensity key. The differences in amplitude when modifying the frequency may be due to the oscillator.

Knowing these reference curves, it is possible to determine the amplitude of any note from the amplitude of only one note.

4.2.3. $\mathrm{dB_{SPL}}$ and $\mathrm{dB_{elec}}$

The musician uses his finger to press on the key, and hears the resulting sound with his ears. We assume that the relevant parameters are force and displacement used when pressing the key, and sound pressure level $\mathrm{dB_{SPL}}$. However, another definition of decibels will also be used, mainly for experimental reasons.

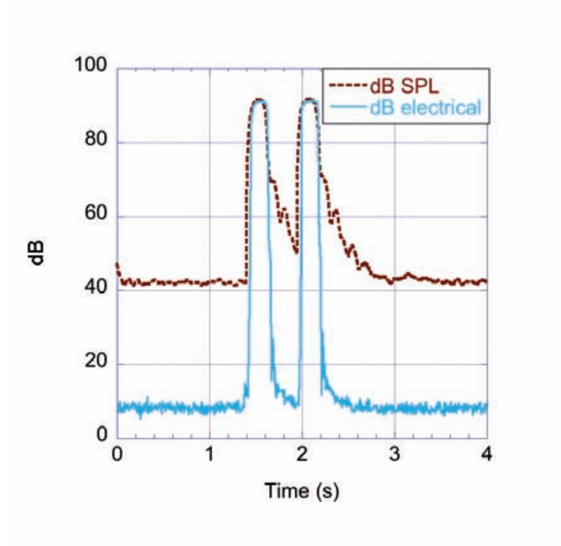

Figure 7: Measurements of the time signals of the electric amplitude after the powder bag, $\mathrm{dB_{elec}}$(solid blue line), and the absolute $\mathrm{dB_{SPL}}$ from the microphone (dash brown line), during a double *staccato*(note C_3), from *no sound* to *fortissimo*, *color online.*

Figure 7 shows measurements of the time signals of the electric amplitude after the powder bag (in decibels: $\mathrm{dB_{elec}} = 20\,log V_{\mathrm{bag}}$), and the *absolute* $\mathrm{dB_{SPL}}$ from the microphone, when a note (here C_3, 130.8 Hz) is performed quickly (*staccato*) twice, from *no sound* to *fortissimo*. The value in $\mathrm{dB_{elec}}$ has been shifted by a constant value of 92 dB to show a superposition of the curves each time the key is pressed. When the key is released and no more sound is produced, $\mathrm{dB_{SPL}}$ decreases slower than $\mathrm{dB_{elec}}$ because of the room response and stops decreasing when it reaches the value of 45 $\mathrm{dB_{elec}}$which corresponds to the background noise level.

As a first approximation, because the electrical signal used inside the Ondes Martenot is sinusoidal (timbre "O"), the difference between $\mathrm{dB_{elec}}$ and $\mathrm{dB_{SPL}}$ depends only on the room response. The constant value of 92 dB between $\mathrm{dB_{elec}}$ and $\mathrm{dB_{SPL}}$ is related to the amplifier's electrical response, the speaker's electroacoustical response, and the microphone's sensitivity. Therefore, $\mathrm{dB_{elec}}$ is preferred to $\mathrm{dB_{SPL}}$ in order to avoid room response and take into

Table I: The different "rise time" of performing $C3_a$ to $C3_h$.

	time (sec)
$C3_a$	4.5
$C3_b$	4.5
$C3_c$	3.6
$C3_e$	2.6
$C3_d$	2.4
$C3_h$	1.1
$C3_g$	0.24
$C3_f$	0.13

account the 33 dB of extra information (below the background noise level).

4.2.4. Amplitude VS Displacement

Figure 8 shows the variations of dB_{elec} according to the key's displacement when pressed. The case when the key is released has not been investigated in this work. A single note (C_3) has been performed several times, from *no sound* to *fortissimo*. The "rise time" (time to perform all the dynamics) was the varying parameter (see Table I).

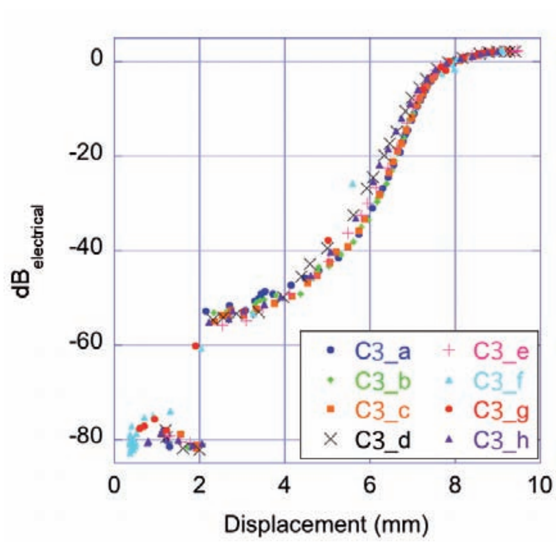

Figure 8: Variations of dB_{elec} according to key's displacement, for a fixed note (C_3).

Firstly, Figure 8 shows that this key provides a huge dynamic range, which corresponds to an audible acoustic range of around 50 dB_{SPL} (the jump from $-80\,dB_{elec}$ to $-55\,dB_{elec}$ for a 2 mm key's displacement, corresponds to the release of the circuit breaker, see Figure 3). According to § 4.2.2, this dynamic range can be extended to each note over the entire range of the instrument. For comparison, [16] shows that the average dynamic range (i.e. the difference between *pp* and *fff* for each note averaged over the entire register) of most traditional instruments rarely exceeds 25 dB_{SPL} .

Secondly, all *instrumental gestures* ([17]) take place in a displacement of only a few millimetres (about between 3 mm and 9.5 mm).

Finally Figure 8 shows that the variation of electrical amplitude according to key's displacement, seems not to depend on the execution speed of the musician (as the curves for $C3_f$ and $C3_g$ do not show any special behaviour with regard to the other notes).

4.2.5. Force VS Displacement

The key's displacement and the force with which it is pressed are linked via the mechanical response of the intensity key. Figure 9 shows the variation of the finger force applied on the key according to the displacement of the key for a single note (C_3) played several times (it corresponds to the same experiments as in Figure 8).

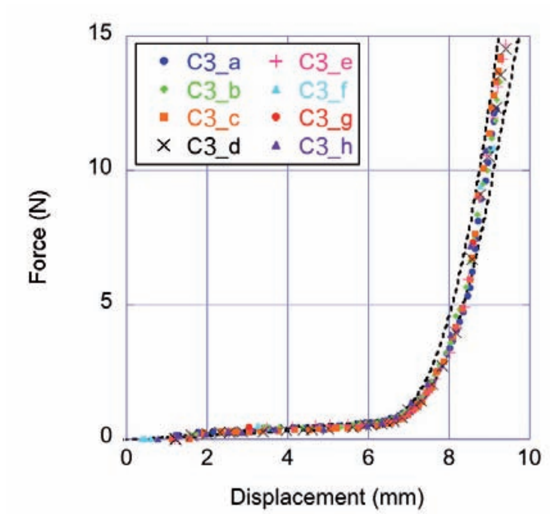

Figure 9: Mechanical response of the key: variation of the finger force applied on the key according to the displacement of the key, for several notes; expanded uncertainty with 95 % confidence interval (dash lines).

Figures 8 and 9 show that great variations of electrical amplitude correspond to great variations of force (highly non-linear with respect to key's displacement). To specify the linked areas between audio dynamics, force, and key's displacement, the dB_{SPL} dynamic range of 50 dB_{SPL} is divided in six equal parts (in the manner of the six musical *nuances*: *pp*, *p*, *mf*, *f*, *ff* and *fff*). The corresponding areas (i.e. at the boundaries between each musical nuance) of key's displacement and of the finger force applied on the key, calculated for notes $C3_a$ to $C3_h$ are reported in Table II (*s.d.* refers to standard deviation to the mean).

Table II: Mean force, mean displacement and standard deviation, calculated from measurements of $C3_a$ to $C3_h$ (see figure 9), corresponding to $\mathrm{dB_{SPL}}$ values of the boundaries of six musical nuances equally distributed over the entire dynamic range of $50\,\mathrm{dB_{SPL}}$.

$\mathrm{dB_{SPL}}$	mean disp. (mm)	mean Force (N)
45.0	4.3 ($s.d.$ 0.15)	0.39 ($s.d.$ 0.06)
53.3	5.3 ($s.d.$ 0.19)	0.47 ($s.d.$ 0.07)
61.6	5.9 ($s.d.$ 0.15)	0.52 ($s.d.$ 0.07)
70.0	6.4 ($s.d.$ 0.15)	0.62 ($s.d.$ 0.08)
78.3	6.8 ($s.d.$ 0.12)	0.82 ($s.d.$ 0.11)
86.6	7.3 ($s.d.$ 0.08)	1.34 ($s.d.$ 0.11)
95.0	8.8 ($s.d.$ 0.05)	9.60 ($s.d.$ 0.30)

Table II shows that only a 4.5 mm displacement is needed (from 4.3 mm to 8.8 mm) to reach the maximum sound intensity ($95\,\mathrm{dB_{SPL}}$) starting from the background noise level ($45\,\mathrm{dB_{SPL}}$). As the instrumental gesture is performed in only a few millimetres, it can be done quickly enough to allow particularly sharp attacks of the notes. Thus, the intensity key controls not only the amplitude of the produced sound, but also all the dynamics of the notes (including attack and decay).
Moreover, the range of efforts required to use the key corresponds to usual forces (around 0.3 N and 3.0 N) that the finger of a musician provides without undue fatigue. The same range has been obtained with violinists pressing on their strings ([18]).

Thus, the special mechanical response of the intensity key appears to be very important to explain how a musician can finely control the large dynamic range of the instrument. A mechanical model is required to deal with this response in depth.

5. Mechanical model

In order to describe the working of the Ondes Martenot intensity key, a 2D quasi-static mechanical model was used. In this model the intensity key consists in (see Figures 3, 10):

- a beam, standing for the elastic strip 1,
- a bar, standing for the most rigid part 2,
- a non-linear spring which reproduces the mechanical behaviour of the powder bag.

Displacement of the intensity key under the musician finger is given by parameter e. The displacement range of the key is divided into two phases. The first phase results in a pure bending of beam 1. During the second phase solid 1 is subjected to complex bending while the powder bag is crushed.

The first phase can be described by a simple beam model, until the contact is made between the key and

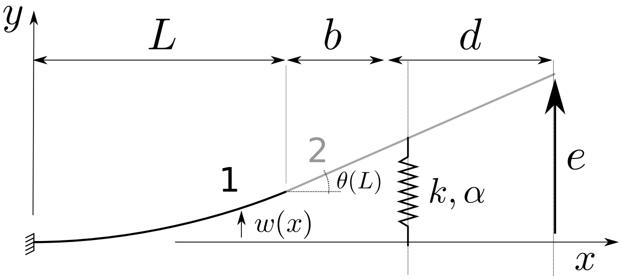

Figure 10: Mechanical model of the key, with beam 1 of length L, bar 2 of length $b + d$.

the powder bag. The next part gives more details for modeling the second phase, after contact has been made.

5.1. Modeling the bag

The powder bag is a complex mechanical structure with granular media and an external elastic membrane. Its behaviour is non-linear when it is crushed. Here we simplify the approach and model the bag using a unique 1D non-linear spring; this approach will be justified in next paragraph. The crushing of the powder bag is given by displacement u. Then the behaviour of the bag is given by the following expression (1):

$$F_k = -ku^\alpha \quad | \quad \alpha > 1 \tag{1}$$

where F_k is the vertical force, and k the constant stiffness of the bag. Non-linearity is controlled by parameter α. For Hertz contact (contact between homogeneous sphere and a plan), non-linearity is characterized by $\alpha = 3/2$. In our model, α is determined in the following to fit experimental data; results will be compared with experimental results obtained on similar bag taken out from the intensity key.

5.2. Equilibrium

Beam 1 is one-side-clamped to the base frame, and clamped to bar 2 at the other end (see Figure 10). It is governed by the following Euler-Bernoulli beam equation:

$$\begin{aligned} EI_{gz}\partial_{xx}w(x) &= M_{fz} \\ &= (L-x)F_{2\to1} + M_{2\to1} \end{aligned} \tag{2}$$

where $w(x)$ is the deflection of the beam at abscissa x, E is the elastic modulus, I_{gz} the second moment of area of the beam cross section, and M_{fz} is the bending moment around $\vec{z}$ axis; M_{fz} expression is given by using $F_{2\to1}$ and $M_{2\to1}$, respectively the force and moment of solid 1 over solid 2. Position of bar 2 is given by the parameters $w_L \equiv w(x = L)$ and $\theta_L \equiv \partial_x w(L)$. Boundary condition at $x = 0$ is: $\partial_x w(0) = 0$.

Solid 2 is put under the forces:

- $\vec{F}_{1\to 2}$, the force of 1 over 2,
- $\vec{F}_k$, the force imposed by the powder bag over 2,
- $\vec{F}_e$, the force of the musician pressing the key.

These vectors will be reduced next to their vertical component. Thus the equilibrium of bar 2 is given by two equations (forces and moment at $x = L$):

$$\left.\begin{array}{r} F_{1\to 2} + F_k + F_e = 0 \\ M_{1\to 2} + bF_k + (b+d)F_e = 0 \end{array}\right\} \tag{3}$$

First and second integration of expression (2) gives two equations on $w(x)$ and $\theta(x) \equiv \partial_x w(x)$ which can be re-written in:

$$\left.\begin{array}{rl} EI_{gz}\theta_L & = L(\xi - d)F_k + L\xi F_e \\ EI_{gz}w_L & = \frac{L^2}{2}(\zeta - d)F_k + \frac{L^2}{2}\zeta F_e \end{array}\right\} \tag{4}$$

with $\zeta = b + d + \frac{2L}{3}$ and $\xi = b + d + \frac{L}{2}$.

Geometrical considerations lead to additional equations:

$$e = w_L + (b+d)\theta_L \tag{5}$$

$$a = w_L + b\,\theta_L \tag{6}$$

where a is the y position of bar 2, with $a = a_0 + u$ (a_0 is the position of the bag top before contact).

By mixing expressions (1),(3),(4),(5) and (6), we obtain the general equation:

$$u + \frac{kL^3}{12EI_{gz}}\frac{d^2}{L_2}u^\alpha = \frac{L_1}{L_2}e - a_0 \tag{7}$$

where:

$$L_1 = \frac{L\zeta}{2} + \xi b$$

$$L_2 = \frac{L\zeta}{2} + \xi(b+d)$$

For simple cases ($\alpha = 1$ or $\alpha = 2$), we get an exact solution of expression (7). In general, expression (7) is derivated with respect to u and gives:

$$\mathrm{d}u\left(1 + \frac{kL^3}{12EI_{gz}}\frac{d^2}{L_2}\alpha u^{\alpha-1}\right) = \frac{L_1}{L_2}\mathrm{d}e \tag{8}$$

Equation (8) is used with an explicit scheme to calculate a small increment du for a small displacement increment de. The identification of the mechanical properties is discussed in the next section.

Table III: Geometrical parameters of the key.

h_1	0.4	mm
b_1	17.5	mm
L	14.0	mm
b	35.0	mm
d	75.0	mm
a_0	$2.^{\pm 0.5}$	mm

5.3. Parameters

Geometrical parameters were measured on the original instrument and are reported on Table III, whereas mechanical properties had to be identified from experimental results on whole key.

Young modulus E of beam 1 is identified on the first linear part of the force-displacement curve (see Figure 11): it was found to be about 200 GPa, which is a common value for steel used in springs. Then the non-linear part of the curve is used to determine parameters k, α, and the correct initial position of the bag a_0 (supposed to be around 2 mm); the least square method fitting gave results of Table IV.

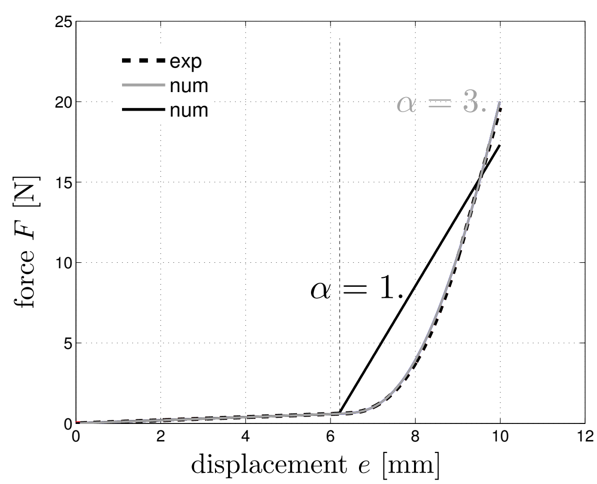

Figure 11: Force-displacement curves: experimental (black dash line), numerical fitting with $E = 200$ GPa, $\alpha = 3., k = 40.0$ N.mm^{-1} (gray solid line), and reference curve $\alpha = 1.$ (black solid line).

Table IV: Mechanical properties and parameters identified by numerical fitting.

E	202	GPa
k	40.2	N.mm^{-1}
α	3.05	
a_0	2.23	mm

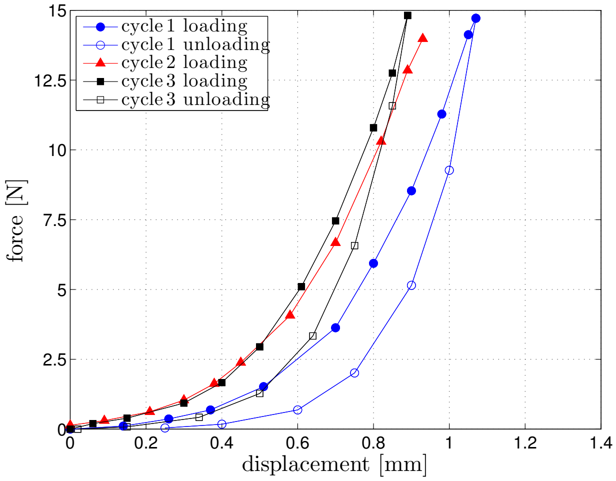

Figure 12: Cyclic force-displacement curves obtained on similar bag from another Martenot instrument, *color online.*

Total displacement u at the bag position was found to be about 1.5 mm. This is in accordance with other measurements on the bag alone ([6]), showing that this amplitude is enough to obtain 450 kΩ of resistance variation (from 466 kΩ to 18 kΩ).

5.4. Experimental validation

In order to assess these results, force-displacement tests were conducted on a similar bag, from another Martenot instrument. Measurements were carried out on a displacement range of 0–1 mm. Significant hysteresis was observed between loading and unloading phases (see Figure 12); settling has also been observed during consecutive cycles. During loading phases only, and by fitting with equation (1), α values were carried out in range [2.5–3.], and k values in range [20.–30.] N.mm^{-1}. This is in accordance with numerical values identified previously by the model into the whole key mechanism. Moreover it shows the relevance of using expression (1) during loading phases, while describing also unloading phases would require further modeling efforts.

The model presented here can be adapted to various geometrical configurations, in order to fit different Ondes Martenot. It could also be integrated in a simulation chain using finger force as entry parameters to compute electrical properties.

6. An early mechanical haptic device

In order to investigate how a musician can finely control the large dynamic range of the instrument, a discussion is proposed about some psychophysical aspects of the intensity key.

6.1. Force applied and force perceived

In Section 4.2.5, Figure 9 shows the variation of the finger force pressing on the key according to the displacement of the key. The key's inertia is considered to be negligible because of its small weight (around 30 g).

Thus, the force F required for the finger to press the key is also the reaction force exerted on the finger by the key. So the intensity key can be seen as a purely mechanical haptic device. Particularly, it acts as a non-linear spring in the "working areas" (4.3 to 8.8 mm ; 0.4 to 10 N).

6.2. Discussion

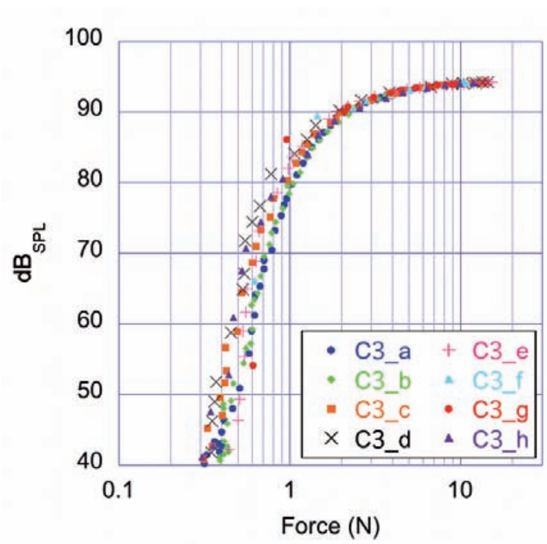

Figure 13: Variation of Sound Pressure Level, according to the pressing force of the finger.

Figure 13 shows the variation of absolute sound pressure level dB_{SPL}(calculated from dB_{elec}, see part 4.2.3), according to the force F applied on the fingertip of the musician. The vertical axis starts at 40 dB_{SPL}, in order to take into account only sound louder than the background noise level (around 45 dB_{SPL}, depending on location). It is a single note (C_3) played several times (it corresponds to the same experiments as in Figure 8). The asymptotic line (after 5 N) corresponds to the fact that there is a maximum force beyond which the musician get tired too quickly. The major part of the curve (under 85 dB_{SPL} and 1.3 N) is quasi-linear.

According to Psychophysics (Weber-Fechner's law, [19]), the psychological sensation perceived S and the physical intensity I_{ph} of a stimulus are linked via the formula : $S = \beta \log I_{ph}$, where β is a constant. Thus, the logarithm of F can be seen as an amount directly proportional to the *reaction force perceived* by the player at his fingertip.

This suggests a psychophysical interpretation of the curve: when the musician manipulates the key, he feels the effects of this action by two simultaneous channels, the auditory channel (by hearing the change in sound intensity, i.e. the decibels increase), and the tactile channel (variation of the perceived force at the fingertip). This key can thus be seen as a haptic device that provides a suitable mechanical feedback for finely controlling sound intensity.

7. Conclusion

In this paper, the intensity key of Ondes Martenot is investigated, in order to understand the particularly sensitive control of sound it offers to musicians. Experimental measurements show that:

- The change in sound intensity of the note only depends on the displacement of the intensity key and the force applied on it (force and displacement are linked by the mechanical behaviour of the key). In particular, it does not depend on the velocity of the musical gesture.
- This key provides a huge dynamic range of $50\,\mathrm{dB_{SPL}}$ for each note over the entire range of the instrument, for only a few millimetres displacement. Controlling the intensity key with great skill provides then a great variety of attacks ranging from *legato* to *percussive sounds*.
- The force required for pressing the key increases with the increase of sound intensity, in a strong non-linear way.

The experimental protocol (repeating single notes at different octaves) may be seen as a bit far from the way of playing in the real life. Nevertheless, this simplified playing can help to clarify basic properties of the intensity key. For example, the whole $50\,\mathrm{dB_{SPL}}$ of dynamics is rarely used *in real playing* (for example, to be heard above an orchestra). But on the contrary, the ability to quickly change a large amount of dynamics, is very often used (for sharp attacks).
The particular mechanical behaviour seems important to understand the fine control exploitable by musicians. A mechanical model has been proposed to simplify the description of the non-linear force-displacement response of the intensity key during loading phases; however it appeared to be insufficient to describe hysteretic behaviour of complex granular medium.
Finally, an interpretation using psychophysical arguments is suggested: this key acts mechanically as a well-chosen non-linear spring, so that it can be seen as a purely mechanical haptic device for finely controlling sound intensity.

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