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Physical and Psychoacoustic Characterization of the Different Types of Attacks on the Accordion

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Summary
Accordion players distinguish between bellows attacks and finger attacks. In bellows attacks the button (or key) is pressed first and the bellows are moved after. In finger attacks, the bellows are set in motion (by pulling or squeezing them) and soon afterward the button is pressed down. In this work these two different and characteristic types of attacks are documented and compared, and the relationships between the control of the instrument, the generated sounds, and how these are perceived are analysed. Finally, a characterization of these two different types of attacks is given in terms of the duration of the attacks, the beginning and ending of the first harmonics and the evolution of some psychoacoustic parameters.

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1. Introduction

In Musical Acoustics, the term "free-reed" refers to a vibrating tongue constructed or mounted in a way that allows it to vibrate back and forth through a slot [1]. Western free-reed instruments include various families: accordions, concertinas, reed organs and mouth organs. Air, generated by breath or by bellows, flows past the vibrating reed and produces the sound.

A very extensive revision of the previous research made on the free reed dynamics is done by Millot and Baumann in [2]: most of the articles dealing with the modelling of free reeds are only concerned with frequency-domain approach and the threshold of reed auto-oscillation [3, 4, 5, 6, 7, 8, 9, 10]. Fewer works deal with the dynamics of the free reed [10, 11, 12, 13, 14, 15]. Several attempts have been made to derive a model for the free reed [2, 16, 17, 18], the last two texts focusing on the particular case of the accordion. And finally, a few articles have developed an approach to the study of the transients of the free reed attacks [2, 19, 20, 21]

In accordion reeds, one of the ends of the tongue is riveted on a metal plate while the other end is free to vibrate in and out of a slot carved in the plate (Figure 1). There is one reed riveted on each side of the plate. Each reed has its own slot. Accordion reeds are inward-striking reeds: they are only activated when the incoming airflow pushes the reed toward the hole of the reed plate. Thus one of the reeds sounds when opening the bellows and the other reed sounds when closing the bellows. Both produce a sound of equal pitch. In the case of medium or large reeds, the opposite side of the slot is completely covered by a strip made of leather or plastic that prevents the passage of air through the hole of the reed tongue that is not activated. The reed plates are mounted on reed blocks.

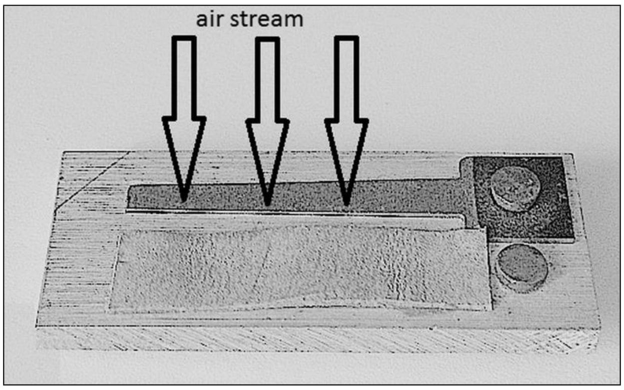

Figure 1. An accordion free reed and a leather strip placed on a reed plate. The same pattern is repeated at the reverse side of the plate but the position of the reed and the slot are inverted.

A modern concert accordion, the so-called free-bass concert accordion, consists of two independent manuals joined by the bellows. Each manual consists of buttons (buttons or keys in the case of the right manual) arranged chromatically, each button giving a single note. The accordion is played by moving the bellows while pressing the buttons. These buttons open the valves (pallets) that allow the airflow to pass through the slot over which the reeds are placed. A free-bass concert accordion contains several groups of reeds, called voices. In the right manual there exist four independent sets of reeds: two central

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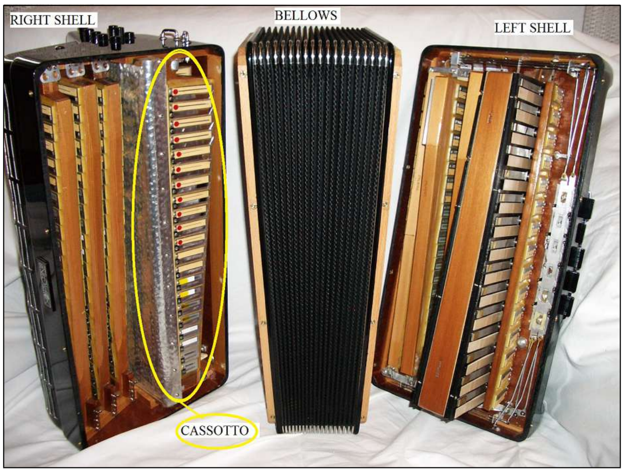

Figure 2. Layout of the blocks of reeds inside the accordion (front view). The *cassotto* or special resonance chamber that attenuates the higher harmonics (marked in an ellipse) is placed inside the right shell.

reeds (8-foot reeds, according to the nomenclature used by organ builders when dealing with organ pipe length and tone), a low-pitch set (16-foot, sounding an octave below the 8-foot) and a high-pitch set (4-foot, sounding an octave higher than the 8-foot). These sets of reeds can be mixed using the registers, up to a total of 15 different combinations. The left free-bass manual consists of three independent registers distributed as 8-foot, 4-foot and 2-foot. In the right manual, both the 16-foot reed and one of the 8-foot reeds are laid out inside a special chamber, called "*cassotto*". The *cassotto* causes the sound emitted by the inner reeds to be warmer than the sound of the outer reeds, because it works as a filter that attenuates the higher harmonics. For frequencies higher than 6000 Hz, our measurements show that there is an approximated 30% attenuation in sound pressure level. There is no *cassotto* chamber in the left manual.

Figure 2 shows the inside of a concert accordion, with three blocks of reeds out of *cassotto* and other three blocks inside *cassotto*, both in the right manual, and the blocks corresponding to the left manual.

Accordion players distinguish [22, 23, 24, 25, 26, 27] between two different types of attacks: hard or finger attacks (the bellows are tightened first and the button is pressed afterwards) and soft or bellows attacks (the button is pressed before moving the bellows). Finger attacks are perceived as more punctuated than bellows attacks, regardless of the dynamics used. Bellows attacks are felt duller than finger attacks, because in bellows articulation the airstream is controlled by the movement of the entire left side of the accordion [22, 23]. Nevertheless, there is a wide range of attacks between hard and soft attacks that an accomplished player can perform. Some examples of attacks have been recorded and are available for interested people.

Similar attacks can be performed on woodwind instruments, depending on the interaction between the tongue and the lips of the performer and the reed [1].

In this work the different attacks of the accordion have been documented and compared, in an attempt to characterize them by analysing the relationships between instrument control, sound generation and sound perception.

In order to characterize the subjective perception of the different attacks, the following have been studied: the duration of the attacks, the onset and offset times of the harmonics, the temporary evolution of the rate of change of the magnitude (in dB) of the pressure and the normalized spectral centroid during the attacks. Although the spectral centroid does not fully describes the timbre (several harmonic spectra with different harmonic distribution can have the same centroid), the spectral centroid has been found to be correlated with the perception of brightness of the sound: the greater the importance of high harmonic amplitudes, the higher the spectral centroid and the greater the brightness of the timbre. We should also take into account that human ear cannot distinguish between two transients less than 10 ms apart [28].

2. Experimental setup

In this work a Pigini Sirius free-bass concert accordion [29] has been used.

The dynamics of the sound has been controlled measuring the sound intensity with an "Extech Instruments 407727" sound level meter placed roughly 50 cm in front of the accordion.

The sounds have been recorded with a Pre-polarized Free-Field ½" Microphone Type 4189-A21 by Brüel& Kjær, placed roughly 50 cm in front of the accordion. Frequency domain and time domain data have been obtained using PULSE Brüel&Kjær software.

The FFT spectra are taken for 6400 frequencies between 20 Hz and 20 kHz, that is, there is an uncertainty of 3.125 Hz in the measurement of the frequency. Record length is 2000 ms and the precision in the measurement of time is 10 ms. The data have been analysed using Matlab. As many harmonics as possible have been obtained for each note. The accordion is an instrument with a broad spectrum and the highest harmonics are likely to depend on the relative position of the accordion to the microphone. But all the measurements were carried out without varying this relative position, which was chosen because it offered a good balanced sound [30]. And finally, the results have been analysed comparing the different types of attacks for this good-balanced-sound position, the same for the complete series of measurements.

An experienced player used to this accordion has been instructed to play the following notes: A2, A#2, B2, A3, A#3, B3, A4, A#4, B4, A5, A#5, B5 of the out-of-*cassotto* 8-foot register of the right manual, each one with *piano* and *mezzo forte* dynamics and with finger and bellows attacks, giving a total of four different combinations per note. Taking previous research [20] into account, the bellows have been always opened (pulled) in our measurements. In fact, when instrumentalists are looking for a quicker or vivid response (especially when they need to stand out a musical accent, or play a forte dynamic), they

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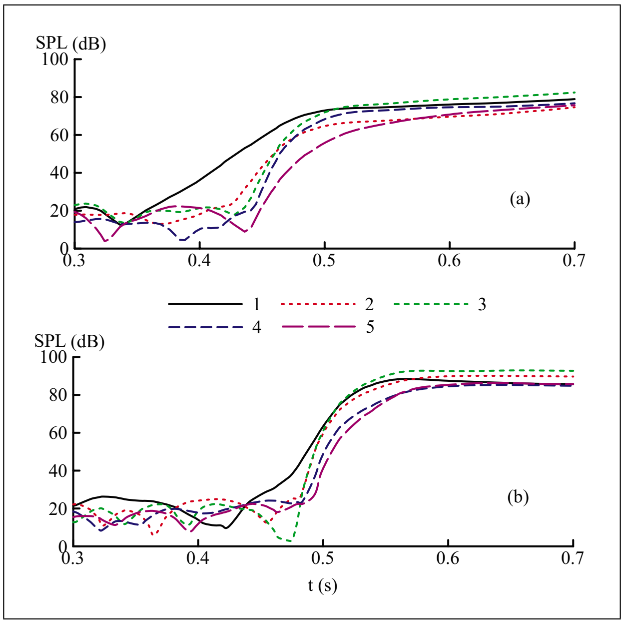

Figure 3. Growing of the first five harmonics for A4 *mezzo forte* (a) bellows attack and (b) finger attack.

usually prefer to play the notes opening the bellows instead of playing them while closing it. The preference probably has a physical or physiological basis: opening the arms seems to be more energetic or innate answer than closing them.

The *piano* and the *mezzo forte* dynamics correspond to about 55 dBA and 70 dBA, respectively, in the sound level meter. The reason for taking three consecutive notes in each octave is to avoid misleading results that could potentially be caused by reeds that are not finely adjusted. Any small change in the shape of the reed or in its adjustment on the reed plate can originate very different attack transients [2, 31, 32].

Apart from that general procedure, the A4 and A#4 notes have been attacked with a slow keystroke (and finger attack and *mezzo forte* dynamics), so as to analyse the effect of the velocity of the finger in the attack transients. And, finally, the possible effect of the *cassotto* in the attacks has been studied for the A4 and A#4 notes (with finger and bellows attack and *mezzo forte* dynamics).

For every type of attack and note, each measurement has been repeated with a minimum of fifteen times.

Those measurements not judged as good by the player were rejected before been taken into account for error analysis.

3. Finger and bellows attacks

As has been pointed out in the introduction, there are two basic different types of attacks on the accordion: the finger attack and the bellows attack (Figure 3). In this section these attacks are analysed using the physical concepts of attack time and spectral centroid.

3.1. Attack Time

A musical sound does not begin at an exact point in time. During the attack of a note the amplitude envelope increases. The Note Onset Time (NOT) is defined as the time when the instrument is triggered to make a sound, whereas the Perceptual Onset Time (POT) is the first time when the acoustic event can be perceived by the listener [33]. The Perceptual Attack Time (PAT) is the instant of time that is relevant for the perception of rhythmic patterns. Gordon [34] studied the perceptual attack time of several orchestral instruments, coming to the conclusion that both rise time and rise slope are important cues to the perceptual attack time. For a tone whose rise time is rapid, perceptual attack time is determined primarily by amplitude cues. If the tone's rise is long, its perceptual attack time is more easily influenced by spectral cues. In the study of the attacks on the accordion, taking into account the different patterns of growing of the harmonics depending on the type of attack (bellows or finger attack), both spectral features and amplitude aspects of the attacks have been included in the experiments.

The attack times of the harmonics of the measured notes were calculated as time intervals ranging from the moment in which they reach the −50 dB threshold of the maximum amplitude (in dB) up to the time in which they reach the −5 dB threshold of the maximum amplitude (in dB). This definition considers the huge dynamic range of human hearing [19].

Table I shows the attack time (T) of the first harmonic for the studied notes. Finger attacks are shorter than bellows attacks, regardless of the dynamics (*piano* or *mezzo forte*) of the attack. The way in which the finger and bellows attacks are created and the definition of the attack time lead to the different lengths of both kinds of attack. This difference in time duration is related to the opening of the valve: as the button is pressed down, the valve is lifted, allowing the air to excite the reeds. In the case of bellows attacks, the valve lifts before the bellows are moved; in the case of finger attacks, the bellows are tightened first and then the valve is opened afterwards.

Regarding the influence of the dynamics on the duration of the attacks, Table I shows that, with the exception of the A3 note, *mezzo forte* finger attacks are shorter than *piano* finger attacks. In the case of bellows attacks, the range of dynamics has no apparent influence on the duration of the attack. The different behaviour of the A3 note could be due to a reed that has not been finely adjusted, as it has been pointed out in the previous section.

No constant behaviour can be observed as far as the influence of the frequency of the note on the duration is concerned. Nevertheless, in technical literature about the accordion there are several references [22, 24, 35] to the fact that low-pitch reeds need a certain time to respond. The apparent contradiction is explained by taking into account that in technical literature about the accordion the time of the response of the reed is defined as the interval going from the moment in which the accordionist triggers the bellows and/or the finger (note onset time) up to the time

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Table I. Values of the frequency and attack time for the first harmonic of all the studied notes.

Note	Frequency f (Hz)	Mezzo forte dynamics Bellows attack T (ms)	Mezzo forte dynamics Finger attack T (ms)	Piano dynamics Bellows attack T (ms)	Piano dynamics Finger attack T (ms)
A2	112.5	450	80	660	110
A#2	112.5	390	70	—	—
B2	125.0	540	100	—	—
A3	225.0	480	110	380	90
A#3	237.5	220	70	440	100
B3	250.0	190	60	380	70
A4	437.5	390	60	410	90
A#4	462.5	440	60	390	140
B4	500.0	390	70	410	120
A5	887.5	610	50	300	60
A#5	937.5	630	50	320	80
B5	1000.0	520	50	320	80
A6	1762.5	510	100	350	130
A#6	1875.0	430	60	330	80
B6	1987.5	590	70	250	80

in which the sound is stable [33]. A part of this time interval is excluded from our definition of attack time, namely, the initial time interval extending from the very moment in which the bellows or the finger are set in motion until the time in which the harmonic we are considering reaches −50 dB of the maximum amplitude (in dB).

Table I shows that there is a wide variation in the attack durations, what could be unexpected for notes differing by only a semitone. This variation is attributed to several factors: the great dependence of the response of the reed on the shape of the reed [32, pp.31-32]; on the adjustment of the reed on the reed plate [31, p.41]; and even on the characteristics and adjustment of the leather or plastic strip that covers the opposite side of the slot of the reed plates for low- and middle-pitched reeds [32, p.61].

This behaviour is consistent with the theoretical study of Millot and Baunman [2] that found different dynamical behaviours when the useful sections of the reed changed. Figure 4 shows the beginning (−50 dB threshold of the maximum amplitude) and the end (−5 dB threshold of the maximum amplitude) of the two kind of attacks, for the lowest harmonics of the A#3 note. As is the case with the first harmonic, it can be seen that bellows attacks are longer than finger attacks for all the studied harmonics.

In *mezzo forte* finger attacks, all the harmonics begin and end almost simultaneously. In *mezzo forte* bellows attacks, harmonics begin almost simultaneously, but end at different instants. In *piano* dynamics, finger and bellows attacks have a similar behaviour: in *piano* finger attacks all the harmonics begin and finish almost simultaneously; in *piano* bellows attacks, harmonics begin and end in an unevenly way.

The rate of change of peak pressure and other dynamic attributes of the sound could play a key role in the perception of attack transients [36]. If the only difference between the two types of attacks were their duration, their respective rates of change of the magnitude (in dB) of the pressure should evolve in the same way. However, taking

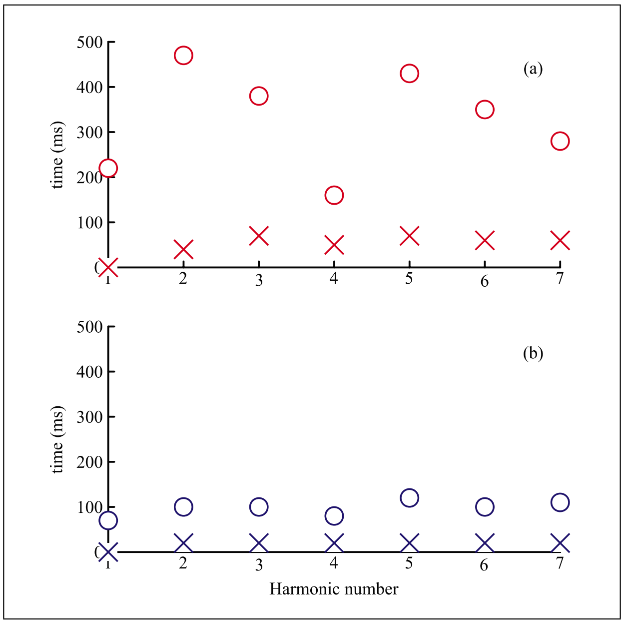

Figure 4. Beginning (x) and ending (o) times for A#3 *mezzo forte* (a) bellows attacks and (b) finger attacks.

the time intervals in equal partitions of the attack time (T) of the first harmonic, one can see that each kind of attack has its characteristic evolution. Figure 5 shows the rate of change of the magnitude (in dB) of the pressure of the two kinds of attacks, for the lowest harmonics of the A#3 note.

Bellows attacks show a high rate of change during the first quarter of the attack time of each harmonic. For the rest of the attack, this rate is very low. However, for finger attacks, this rate of change is more balanced during the entire interval. This fact could contribute to the different perception of the kinds of attacks.

3.2. Spectral Centroid

The spectral centroid is an important spectral timbre descriptor that correlates strongly with the perceived bright-

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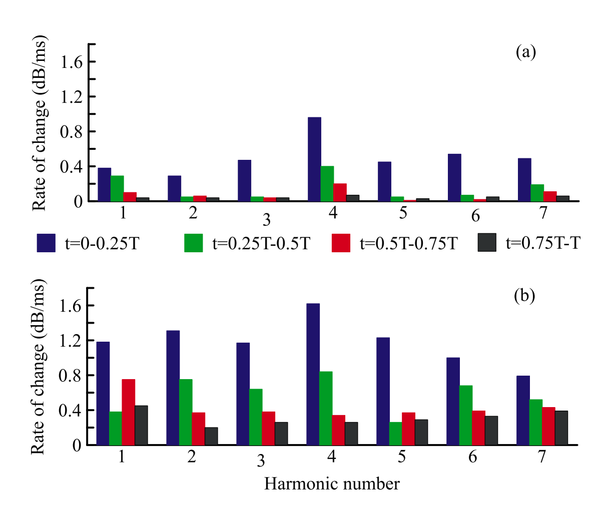

Figure 5. Rate of change of the magnitude (in dB /ms) of the first seven harmonics for A#3 *mezzo forte* for each of the four segments of the attack time T. (a) bellows attacks and (b) finger attacks.

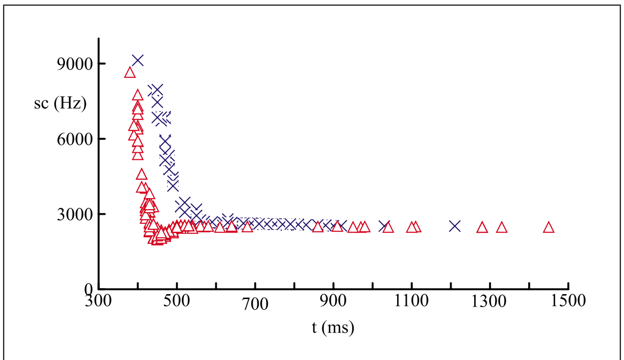

Figure 6. Evolution of the spectral centroid of *mezzo forte* bellows (crosses) and finger attacks (triangles) on the A#3 note. The maximum error in centroid values is ±40 Hz.

ness of a signal [37]. The spectral centroid describes the centre of gravity of the harmonics, weighted with their respective amplitudes. It can be expressed by

$$\mathrm{sc} = \frac{\sum_{k=1}^{k=n} f(k) A_p(k)}{\sum_{k=1}^{k=n} A_p(k)}, \tag{1}$$

where $A_p(k)$ is the amplitude, in Pascals, related to the k-th spectral component. In our case the sum was extended over the whole range of frequencies up to 20000 Hz, so that the former expression is now written as

$$\mathrm{sc} = \frac{\int_{20}^{20000} \mathrm{d}f\, f\, A_p(f)}{\int_{20}^{20000} \mathrm{d}f\, A_p(f)}. \tag{2}$$

An example of the evolution of the centroid with time for finger and bellows attacks can be seen in Figure 6.

The comparison of both attacks might lead to the conclusion that the only difference is their duration (attack time). In order to check this point, Figure 7 shows the evolution of the centroid with the horizontal axis in units of

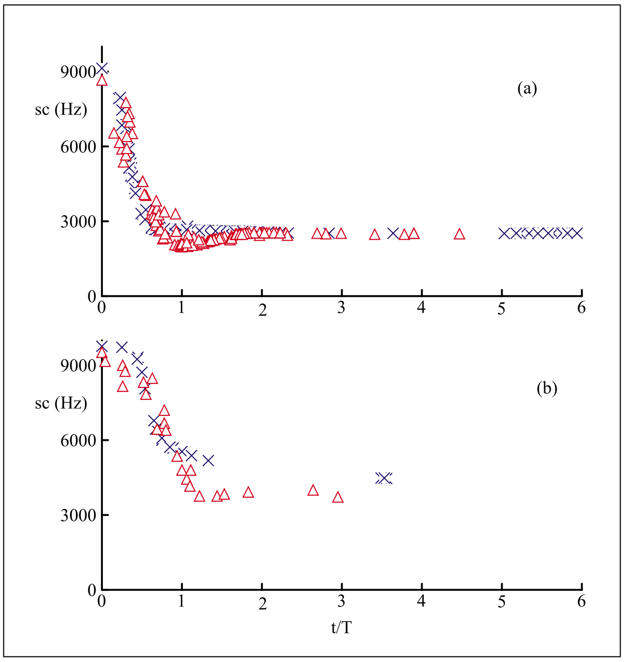

Figure 7. Two examples, (a) A#3 *mezzo forte* and (b) A4 *piano*, of the temporal evolution (in units of attack time) of spectral centroids during the attack. Crosses correspond to bellows attacks and triangles to finger attacks. The maximum error in centroid values is ±40 Hz.

the attack time (t/T), where T is the attack time of the first harmonic, different for each type of attack. If the only difference between the two types of attack were their duration, both centroids should evolve in the same way. However, the graph shows that the centroid of the bellows attack always remains over that of the finger attack for both *mezzo forte* and *piano* dynamics.

In *mezzo forte* dynamics, at the beginning of the attack the centroid value is near 8500–9000 Hz. This is true for both types of attack. For the finger attack the centroid varies more rapidly at the beginning, reaching a minimum, and then it rises slowly. The most significant difference between finger and bellows attacks lies, approximately, between $0.7T$ and $1.7T$, when the centroid of the finger attack is lower than the centroid of the bellows attack. At the end of the attack all the centroids are close to 2500 Hz. The fact that the centroid of each type of attack evolves in a different way during some part of the attack is an indicator of a different evolution of the timbre; nevertheless, it does not necessarily implies that this difference can always be perceived. More information about the limen of the centroid would be needed before making such a categorical and general assertion.

The time interval in which the centroid of the finger attack is lower than the centroid of the bellows attack seems to be slightly different depending on the pitch of the attacked notes, but that difference between both types of attacks is an identifying characteristic. Particularly, for the lowest notes the beginning of the characteristic time interval seems to be more delayed as compared to the middle or high ones. The initial descending slopes of both cen-

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troids are less steep than those of the middle range notes and the time interval in which the centroid of the finger attack is lower than the centroid of the bellows attack has moved slightly to higher values of time. Due to this fact, the attacks on low-pitch notes are likely to be felt as more sluggish by listeners and players [22, 24, 37].

In any case, for any given pitch, the values of the centroids associated with bellows and finger attacks approach a common value at the end of the attack, as it should be, since the way in which the note is attacked only has an effect on the transitory part of the sound.

In the case of *piano* attacks, there is also a time interval in which the centroid of the finger attack is lower than the centroid of the bellows attacks.

In the case of the highest notes analysed here (A#5, B5, A6, A#6, B6), the temporal evolution of the centroids corresponding to the *piano* bellows and finger attacks does not show a clear difference that allows to identify the type of attack. Anyway, the final state of each pair of bellows and finger attacks always has a common centroid value.

4. Finger attacks performed with slow keystroke

The hardness of an attack, the amount of punctuation at the beginning of a tone, can be modified by varying the speed with which the button is pushed down [22, 27].

In the case of a normal finger attack, the finger strikes the button rapidly (the button is pushed down as fast as possible) and the bellows are tightened before the finger acts. Therefore the air canal through the chamber of the reed is completely free. Normal finger attacks last 0.05 s approximately. Slow attacks can be performed as slow as wished, but their duration is around 0.50 s.

In the case of a finger attack with a slow keystroke, the button is slowly depressed. The bellows are also tightened before the finger attacks, but the air canal is now opened slowly, according to the velocity of the button, and the airflow increases less rapidly than in the case of a normal (rapid) finger attack. This initial small aperture of the valve can exert some influence not only in the starting dynamics, but also in the beginning spectrum, favouring some harmonics, which could be reflected in some psychoacoustics parameters such as the spectral centroid.

Some measurements have been made to analyse the attack time and the rate of change of the magnitude (in dB) of the pressure of the first harmonics for *mezzo forte* bellows and finger attacks, with slow keystroke, of the A4 and A#4 notes.

Table II shows the values obtained for the attack time (T) of the first harmonic for finger attacks performed using slow keystrokes for the A4 and A#4 notes. Values obtained with normal finger attacks and bellows attacks are depicted for comparison. These results show that when the velocity of the button decreases, the attack time takes an intermediate value between those obtained for finger and bellows attacks. One can say that the finger attack "gets softened".

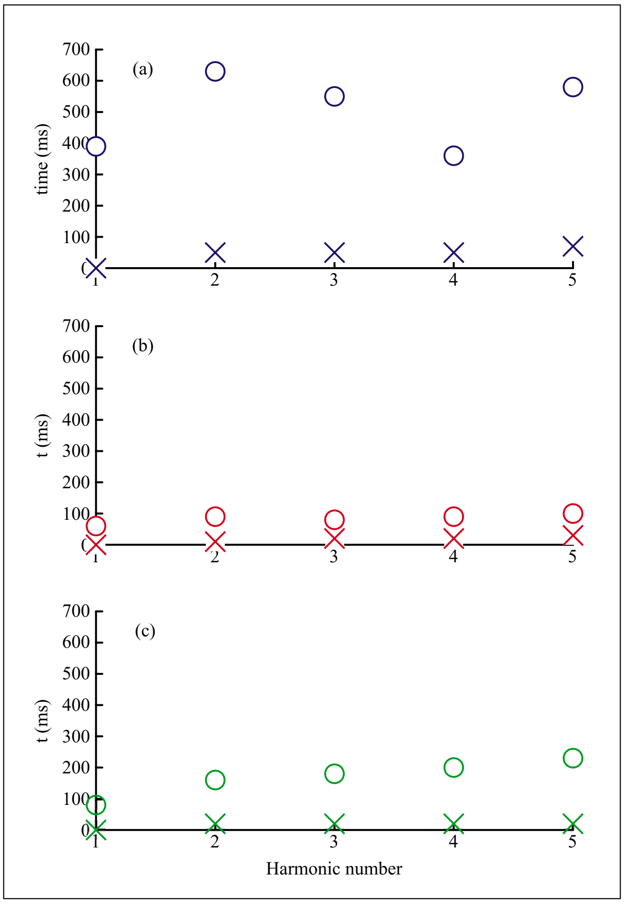

Figure 8. Beginning (x) (−50 dB threshold of the maximum amplitude) and end (o) (−5 dB threshold of the maximum amplitude) of the first harmonics of the A4 note for (a) normal finger attack, (b) finger attack performed using "slow keystrokes", and (c) bellows attack in *mezzo forte* dynamics.

Figure 8 shows the beginning (−50 dB threshold of the maximum amplitude) and the end (−5 dB threshold of the maximum amplitude) of the first harmonics of the A4 note for (a) normal finger attack, (b) finger attack performed using "slow keystrokes", and (c) bellows attack. All the measurements correspond to *mezzo forte* dynamics. As it happened with the first harmonic, when the velocity of the button decreases, the attack times lay again between those obtained for finger attacks and those measured for bellows attacks. These results corroborate that a slow lowering of the button on a finger attack softens the attack: the attack time of the finger attack is lengthened and the evolution of the harmonics shows an intermediate behaviour between that of finger attacks and bellows attacks.

The effect of the slow attack on the button is also reflected in the rate of change of the magnitude (in dB) of the pressure of the first harmonics, turning the normal rate of change of the magnitude (in dB) of the pressure of harmonics of the finger attacks into a rate of change that resembles that of the bellows attacks (Figure 9).

When comparing bellows and finger attacks on the same note with the same dynamics, it was seen that the centroid of a bellows attack always remained over the centroid of the corresponding finger attack and there was a character-

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Table II. Values of the frequency (Hz) and attack time T (ms) for the first harmonic of A4 and A#4 notes for finger attacks performed with slow keystrokes compared with the values obtained for finger and bellows attacks.

		Mezzo forte dynamics			*Piano* dynamics		
Note	f (Hz)	Bellows	Finger (slow)	Finger	Bellows	Finger (slow)	Finger
A4	437.5	390	80	60	410	220	90
A#4	462.5	440	150	60	390	180	140

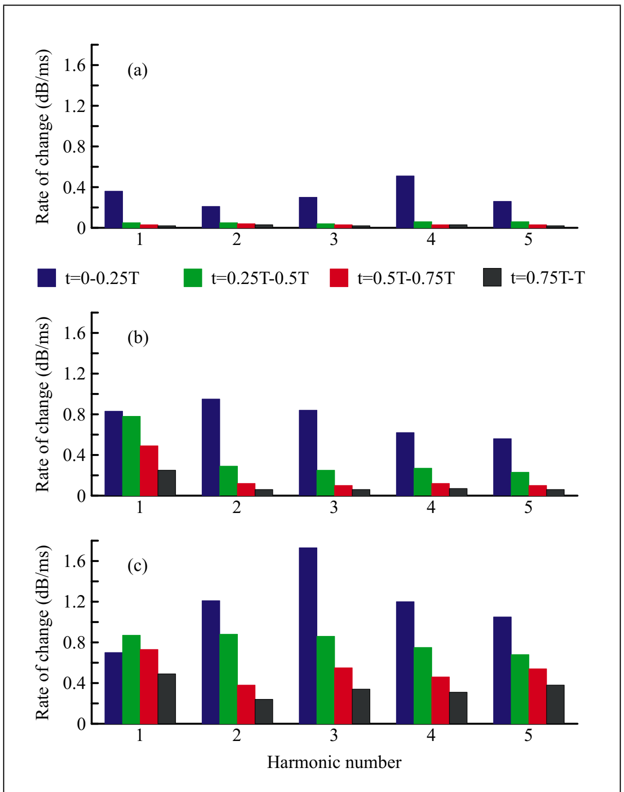

Figure 9. Rate of change of the magnitude (in dB) of the pressure of the first harmonics of the A4 note for (a) bellows attack, (b) normal finger attack, and (c) finger attack performed using slow keystrokes, all of them in *mezzo forte* dynamics.

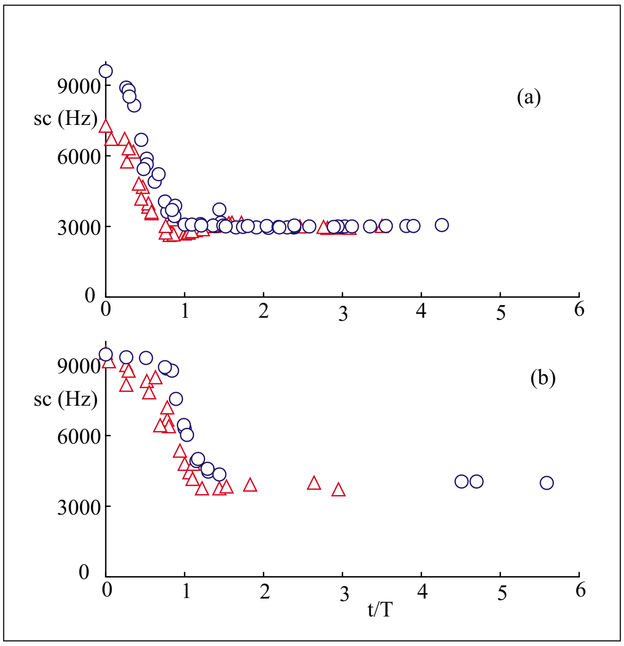

Figure 10. Spectral centroid vs. time in units of the attack time corresponding to (a) *mezzo forte* attack and (b) *piano* attack of the A4 note. Triangles correspond to normal finger attacks and circles to finger attacks performed using slow keystrokes. The maximum error in centroid values is ±40 Hz.

istic time interval in which the centroid of the finger attack was significantly lower than the centroid of the bellows attack.

The effect of a slow keystroke on a finger attack is reflected in the centroid (Figure 10) as an increase of its values. Firstly, the centroid of the slow-keystroke attack remains over the centroid of the normal finger attack and, secondly, there is no characteristic time interval that tells apart the centroid of the slow-keystroke attack from the centroid of the bellows attack. The slow keystroke seems to soften the finger attack and apparently models the air flux of a finger attack softening the characteristic zone that distinguishes it from the bellows attack.

5. Attacks performed in *cassotto*

As mentioned in the introduction, the *cassotto* is a special chamber in which two of the sets of reeds of the right manual are laid (see Figure 1).

The *cassotto* rounds the higher harmonics giving a warmer timbre. It acts on the sound generated by the reed, but not on the reed itself. Hence, it was expected that the *cassotto* would have no influence on the relative duration and behaviour of bellows and finger attacks. This is coherent with the absence in technical literature about the accordion of any warning about avoiding or preferring the use of *cassotto* registers as far as the response of the reeds is concerned. *Mezzo forte* bellows and finger attacks were performed on the A4 and A#4 notes of the 8-foot register inside *cassotto*, so as to compare them with the same kind of attacks performed on the same A4 and A#4 notes belonging to the 8-foot register out of *cassotto*.

Table III shows the values obtained for the attack time (T) of the first harmonic for *mezzo forte* bellows and finger attacks performed on the A4 and A#4 notes inside *cassotto*. Values obtained for the attacks on the same notes but out of *cassotto* are also depicted for comparison. The *cassotto* has no effect in the total length of the attacks. The obtained results are similar to those depicted in Figure 4.

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Table III. Values of the frequency and attack time for the first harmonic of A4 and A#4 notes (inside and outside *cassotto* chamber) for finger and bellows attacks in *mezzo forte* dynamics.

Mezzo forte dynamics		Out of *cassotto*		Inside *cassotto*	
Note	f (Hz)	Bellows T (ms)	Finger T (ms)	Bellows T (ms)	Finger T (ms)
A4	437.5	390	60	480	60
A#4	462.5	440	60	320	60

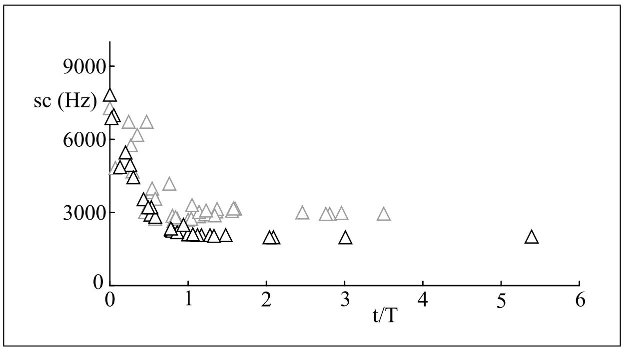

Figure 11. Spectral centroid vs. time in units of the attack time corresponding to *mezzo forte* finger attacks performed on the A4 note of the 8-foot *cassotto* register (black triangles) and the same note of the 8-foot register out of *cassotto* (grey triangles). The maximum error in centroid values is ±40 Hz.

The effect of the *cassotto* in the high harmonics can be observed in the lower value of the respective centroid (Figure 11).

When comparing the centroids of the attacks performed on the notes inside the *cassotto* chamber, it can be seen again that, the same as in Figure 7, there is a range of time in which the centroid of the finger attack goes under that of the bellows attack. In any case, the distinctive zone does not seem to be as clear as in the case of bellows and finger attacks on the reeds out of the *cassotto* chamber. The way in which the *cassotto* attenuates the higher harmonics results in a softening of the differences between the spectral centroids corresponding to finger and bellows attacks. Moreover, as it was the case with attacks performed on reeds placed out of the cassotto chamber (see Figure 7), bellows attacks show again a high rate of change of the magnitude (in dB) of the pressure during the first quarter of the attack time of each harmonic. For the rest of the attack, this rate is very low. However, for finger attacks, this rate of change is more balanced during the entire interval.

6. Discussion

Some qualitative ideas about the attacks can be derived from the analysis of the process of creation of each type of attack. In the finger attack the bellows are tightened first. This implies that a difference of pressure is created between the outside and the inside of the accordion. If a button is lowered at that moment, the corresponding valve will open the chamber of the reed and the air of the surrounding space will flow through that reed, generating the sound. Once the bellows are tightened, the velocity at which the button is lowered becomes the parameter that regulates the suddenness of the air movement. The growing aperture generated by the lowering of the button is the only obstacle hampering the passage of air from one region to the other (through the reed). As the finger can push down the button very quickly, the attack is felt as almost instantaneous.

In the bellows attack, the air is forced again to move between two regions of different pressure, but in this case the button has been lowered from the beginning. Therefore, the more or less rapid activation of the bellows is now the factor that determines the suddenness of the attack. Since the bellows have much more inertia than the buttons, the bellows attack is felt more sluggish than the finger attack. Nevertheless, nothing hinders the passage of the airflow, since the button has remained completely open from the beginning of the attack.

The different inertia of the button and the bellows is reflected in the way in which harmonics grow (see Figure 3). The harmonics of a sound generated by a bellows attack have a minor growing slope than the harmonics of the corresponding finger attack. This is closely related to the fact that the spectral centroid of a finger attack has an initial slope steeper than the initial slope of the corresponding bellows attack.

The way in which each attack is produced suggests a different form of external blowing pressure. The finger attack is similar to a Heaviside-step-like blowing pressure and the bellows attack could be represented by a ramp-like pressure. Such kind of research has been done by Bergeot *et al.* for the clarinet [38, 39].

Transitory effects are also included in the modelling of a free reed by Millot and Baumann [2]. They focus on the comparison of three models of useful sections for the free reed, where the upstream flow would correspond to a finger attack. A related work, for outward-striking reeds, was carried out by Tarnopolsky and Fletcher [7], who studied the threshold behaviour and large-amplitude oscillation of an outward-striking reed in air environment. Their model, just as the model described by Millot and Baumann, depends significantly on the detailed geometry of the reed.

Finally, the different pattern of growth for the finger and bellows attacks, shown in Figure 3, is also reflected in the rate of change of the magnitude (in dB) of the pressure. This has a more balanced growth in finger attacks. Bellows attacks show a high rate of change of the magnitude (in dB) of the pressure during the first quarter of the attack time of each harmonic. In the bellows attack (Figure 3a), the harmonics grow rapidly in the first part of the

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attack and then experience a slower growth. However, the harmonics of the finger attack (Figure 3b) not only have a faster growth than the harmonics of the corresponding bellows attack, but a growth that can be described as more uniform.

As far as finger attacks with a slow keystroke are concerned, the button, and its corresponding valve, is lowered slowly. The lower the speed of the keystroke, the longer the time that takes the airflow to pass as freely as in a normal finger attack. But there is another feature peculiar to this type of attack. If the bellows are firmly tightened (*mezzo forte* or *forte* dynamics) before the action of the finger at the beginning of a finger attack with a slow keystroke, and the button is pushed down very slowly (in order to accentuate the effect of the slow keystroke), a very quick airflow tries to flow through a very small aperture (the gap between the valve and the reed block). Therefore, a Venturi effect can be originated, hindering the raising of the valve, that is, the lowering of the button. The player feels the button to be harder than in normal conditions and the beginning of the attack can be unstable. This instability could also influence the initial spectrum of the sound. Further research on this aspect should be conducted by carrying out measurements inside the accordion.

Several references of technical literature about the accordion include the different perception of the different types of attacks. In [27], for example, some onomatopoeic analogies are described between the different types of articulation (bellows or finger) and the lingual articulation of a singer. The bellows attack is compared with an /aa/ sound; the finger attack is assimilated to a /'ta/ sound.

This can be firstly explained by the way in which each attack is produced and is reflected in the shorter attack time of the harmonics of finger attacks as compared with the corresponding bellows attacks. Secondly, in finger attacks, all the harmonics begin and end almost simultaneously, while the endings of the harmonics of bellows attacks extend over a longer period of time. This characteristic causes finger attacks to be perceived as harder and shorter than bellows attacks. Thirdly, the centroid of a finger attack shows a steeper initial slope than that of the centroid of the corresponding bellows attack. This can also contribute to the fact that the attacks are perceived differently by the listener. Finally, it was shown that bellows attacks show a high rate of change of the magnitude (in dB) of the pressure during the first quarter of the attack time of each harmonic, while finger attacks have a more balanced rate of change for the whole interval. Again, this can contribute to their different perception by a listener.

In the same reference finger attacks with a slow keystroke are assimilated to a /wua/ sound. This softer beginning of the sound can be explained by the longer attack times of these attacks (as compared to the normal finger attacks) and by the modifications that the slow lowering of the button causes in the spectral centroid and in the rate of change of the magnitude (in dB) of the pressure.

Composers can take advantage of the more punctuated character of the finger attacks to play different articulation markings for different melodies in the same hand [25]. This is crucial in the accordion, since the bellows determine the dynamics of both hands (with the exception of a small effect on the dynamics achieved varying the depth up to which the buttons are pressed): if the bellows are used for articulation, they have an effect on the performance of all the reeds [23].

7. Conclusions

The fine differences in timbre have been studied for two different and characteristic types of attacks (bellows attack and finger attack) on a concert accordion. The timbre descriptors selected are the attack time and the spectral centroid. The temporal behaviour of the sound pressure level of the first harmonics has also been characterized. In finger attacks, all the harmonics evolve in a homogeneous way in duration, beginning and ending times, and growth rate of the magnitude (in dB) of the pressure. The attack times of bellows attacks are longer than the attack times of finger attacks. In bellows attacks, harmonics begin almost simultaneously, but they end at different instants. Moreover, this kind of attack also features a high rate of change during the first quarter of the attack time of each harmonic, this rate remaining very low for the remaining duration of the attack.

As far as centroids are concerned, for *mezzo forte* attacks, there is a region of relative times in which the centroid of the finger attack is lower than the centroid of the corresponding bellows attack. In *piano* attacks, the distinguishing zone is not so clear. These characteristics, related to the two different ways to open the valve and the corresponding entry of the flux of air in each kind of attack, could contribute to the different perception of the two kinds of attacks.

Finger attacks performed with a slow lowering of the button bear a certain resemblance to bellows attacks. The *cassotto* has no effect on the duration or behaviour of the attacks. Both results are consistent with the descriptions of the accordion techniques found in the technical literature about the instrument.

In agreement with studies about the modelling of perceptual attack time, the pattern of growth of the first harmonics seems to play a crucial role in the differentiation between bellows attacks and finger attacks.

In our work about attack times we have limited ourselves to time intervals ranging from the moment in which they reach the -50 dB threshold of the maximum amplitude (in dB) up to the time in which they reach the -5 dB threshold of the maximum amplitude (in dB). Future work is intended to include the study of the transient from the very first moment in which the button is pressed (finger attack) or the bellows started (bellows attack).

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