PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Sympathetic vibration in a piano

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Abstract

Sympathetic vibration is a common phenomenon in musical instruments. In the piano, strings that are not struck directly by the hammer can vibrate sympathetically due to physical coupling. This effect will, for instance, occur when the *una corda* pedal is used in a grand piano. When depressed, the hammer shifts rightwards so that the leftmost string will be missed, striking only 1 out of 2 (or 2 out of 3) strings in a note at a same time. In order to understand the acoustical and perceptual differences in the notes played without and with *una corda* pedal depressed, the recordings of a piano for these two playing conditions are studied for all 88 keys. Differences arising in the frequency domains are found and presented alongside with discrepancies in three psychoacoustical descriptors, namely log-attack-time, temporal centroid and normalised spectral centroid. Future work in the form of listening test is planned.

Keywords: piano, sympathetic vibration, una corda pedal, psychoacoustics

1 INTRODUCTION

Sympathetic vibration is a physical phenomenon where a vibrating body that is initially at rest responds to another vibration in vicinity. In string-based musical instruments, sympathetic vibration is a common occurrence as strings vibrate sympathetically due to the excitation of other strings [1, 2]. In the piano, sympathetic vibration of strings is present passively and can also be triggered manually. The passive sympathetic vibration comes in the form of front and rear duplex strings, where extra portions other than the main vibrating part of the string are not damped [3]. This technique was first invented by Steinway and are most commonly seen on the higher registers of a piano. Another passive sympathetic vibration, called "aliquot stringing" is seen exclusively in Blüthner pianos, where an extra fourth string is added to the existing trio of strings, but is left unstruck by the hammer.

The other sympathetic vibrations in the piano are activated by the use of pedals. In a normal playing situation, when a key is played, the corresponding damper is lifted above the specific strings to allow their vibration. However, if the sustain pedal is depressed, the dampers of all notes are lifted and all strings could vibrate sympathetically even if only one key is played. On the other hand, the *una corda* pedal (UC) that is normally seen only in grand pianos, shifts the hammer rightwards when depressed, causing the hammer to miss the leftmost string. As a result, only 1 (out of 2) or 2 (out of 3) strings are struck with the remaining one vibrating only sympathetically [4]. The use of UC pedal, which is required in certain repertoires, has been known anecdotally to create a "more lyrical" tone [4].

Despite being a rather integral part of the instrument, there remains a gap of knowledge in the perception of the use of the UC pedal. The current project aims to identify how the two tones, i.e. those played with and without UC pedal, can be differentiated acoustically and perceptually. To that end, piano sounds of these playing conditions are analysed and early results are presented in this paper. Details of how the sound samples are collected are discussed in Section 2. In Section 3, the signals are compared in the frequency domains, and also by computing psychoacoustical descriptors. Future efforts on how to capitalise current findings are also discussed in Section 3 before a concluding remark in made in Section 4.

2 METHODS

The piano recordings to be analysed are made in an anechoic chamber. The piano used is an Ant. Petrof AP275 and samples of all 88 notes played with and without UC pedal are obtained. The piano sounds are recorded at 44,100 Hz using a Schoeps MK2 microphone. Denoting the direction where the keyboard extends from lowest to the highest note as positive x-direction, its perpendicular (almost parallel to string direction) as positive y-direction and the vertical height as z-direction and taking the leftmost and nearest tip (to the keyboard) of the soundboard as x=0 and y=0, and $z = 0$ at ground level as the origin of the coordinate system, the position of the microphone is approximately (1.3,1.0,1.7) m. The playing force is adjusted so as to give a subjective *mezzopiano* dynamic level.

The UC pedal of the AP275 is set up differently compared to the conventional way. Instead of shifting the hammer rightward to miss the leftmost string completely, the hammer would shift by an amount such that when the keys are played, the edge of the hammer will graze the leftmost string slightly and lightly exciting it. At the same time, the hammer strikes the other string(s) on its softer less used surface, resulting in a different excitation.

Two types of analyses are conducted. The first one is spectral analysis of the recordings. Fast Fourier Transform (FFT) and Short Time Fourier Transform (STFT) between the different playing conditions are used to identify the differences between the two tones. Next, the Timbre Toolbox [5] is used for psychoacoustical analysis. The Timbre Toolbox calculates various psychoacoustical and audio descriptors that are relevant to timbre. The calculations can be made based on several spectral representations and in this paper, only the "STFT amplitude" representation is used. For all signals, Hamming windows of 20 ms duration and 10 ms hop size are used.

In this paper, the two playing conditions are coined with the nomenclature "UC" to indicate that the sound is played with the UC pedal depressed, and "NP" to indicate the normal playing condition. For both conditions, the sustain pedal is not being used.

3 RESULTS

3.1 Spectral analysis

The differences of sound pressure level in the frequency domain between an NP and UC sound of 3.8 seconds are shown in Figure 1. The red line indicates the fundamental frequencies of each key as computed by the YIN estimator [6]. The plot is capped to ± 6 dB even though in some instances, the differences could be as large as 30 dB. In general, the fundamental harmonic is comparable in amplitude but the higher harmonics of the NP sound are usually higher in amplitude. In some cases, such as for keys between 30 to 50, some of the higher harmonics of UC tone are larger in amplitude between keys 30 to 50.

Despite these differences, one should be cautious about the findings as some of these harmonics lie below the threshold of hearing. For example, for key 33 (F3), the FFT for both playing conditions are shown in Figure 2 together with the threshold of hearing [7]. As the microphone was not calibrated, it might be possible that the harmonics up to 4,000 Hz can still be audible. However, beyond that, the harmonics are well below the threshold of hearing and any differences, such as those between 5,500 to 7,500 Hz, will not be audible. In most keys, harmonics beyond 4,000 Hz or so are already below the threshold of hearing.

Figure 3 shows the difference of sound pressure level in dB between NP and UC tones in a Short Time Fourier Transform (STFT) plot for key 33. A Blackman window of length 25 ms is used with a hop size of 5 ms. The STFT plot reveals a few interesting observations. In the attacking phase (approximately between 0.05 s and 0.2 s), the first 5 harmonics (up to 1,000 Hz) are largely similar in terms of amplitude between the two types of tones. However, the next 15 or so harmonics (up to 4,000 Hz) are generally higher in amplitude for NP playing condition. Beyond that range, the signal-to-noise ratio deteriorates and prevents further interpretation. The amplitude comparison for the first 20 harmonics can also be inferred from Figure 2.

After the attacking phase, the amplitude difference reverses for all of the harmonics. Different harmonics in the UC tone exhibit higher amplitudes at different times. This is due to the different decaying rates between

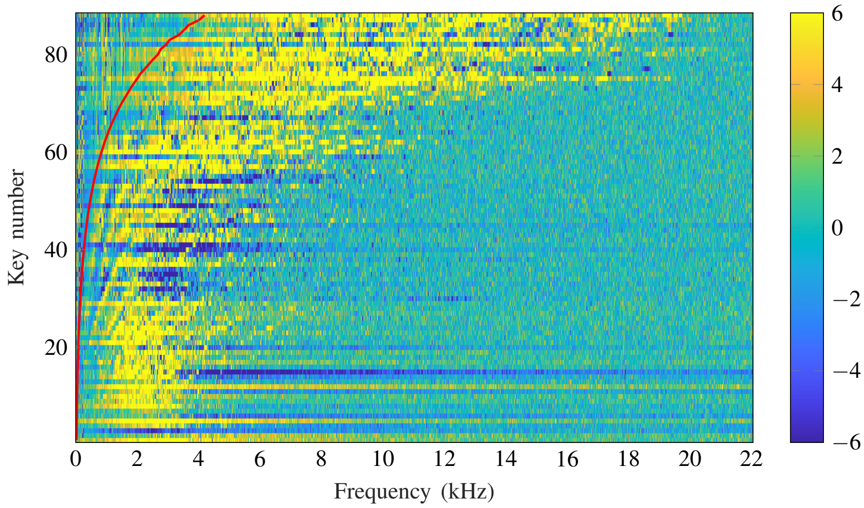

Figure 1. The difference of sound pressure level in dB for all notes between the FFT of a sound that is played normally and a sound that is played with the UC pedal. The red line shows the fundamental frequencies of each key. Positive values (in shades of yellow) indicate higher amplitudes for NP and negative values (in shades of blue) indicate higher amplitude for UC.

the two playing styles. For example in Figure 4 where the SPL of the 12th harmonic is plotted against time, a distinct double decay pattern for the NP tone, i.e. a sharp decay until 1 s, followed by a slower decay, is observed. The double decay pattern is much less obvious in the UC tone but exhibits stronger beating.

The difference in decay pattern can be attributed to how double decay, a distinctive piano sound characteristic, could originate. As a piano hammer strikes a trio of strings of the same note in an NP condition, the energies imparted into each string are largely in-phase with each other, which are quickly dissipated to the soundboard, forming the "attack" sound. However, the frequencies of the strings of the same note are tuned slightly different. This difference causes the strings to vibrate out-of-phase between each other, where the amplitudes of the strings would cancel the net force applied to the soundboard, hence slowing down the dissipation process and forming the "sustain" sound. When a UC pedal is depressed, only the energy of two strings is dissipated to the soundboard, hence weakening the attack. The sympathetic string does not begin vibrating in-phase with the struck string, hence prolonging the sustain phase and exacerbating the beating.

3.2 Psychoacoustical differences

In this section, the sound recordings are analysed using the Timbre Toolbox [5] and several selected psychoacoustical descriptors are presented. These include two global descriptors, i.e. log-attack-time (LAT) and temporal centroid (TC) as well as one time-varying descriptor, i.e. the normalised spectral centroid (NSC). This part of the investigation is inspired by the work by Chaigne et al. [8], which also includes a concise overview of the various perceptual and acoustic analysis literature on piano tones.

The log-attack-time describes the length of the attack phase and is defined as:

$$\mathrm{LAT} = \log_{10}(t_{end} - t_{start}), \tag{1}$$

where t_{end} and t_{start} are the ending and starting time of the attack as calculated in the Timbre Toolbox respectively. The estimation of these values is based on the envelope of the signal, with its algorithm detailed in [5]. With time signal t_n, the envelope signal, $e(t_n)$, is obtained by computing the root-mean square amplitude of each sound signal with a window of 20 ms, instead of a low-passed analytical signal with cut-off frequency at

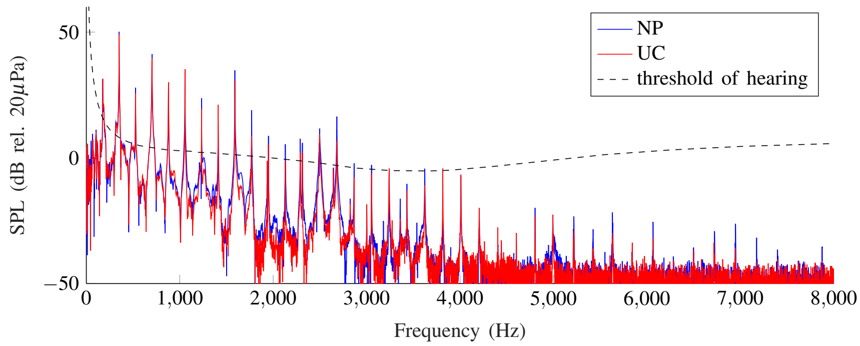

Figure 2. The power spectra (expressed in dB SPL) for key 33 (F3) for both NP and UC playing conditions. The black dotted line shows the threshold of hearing.

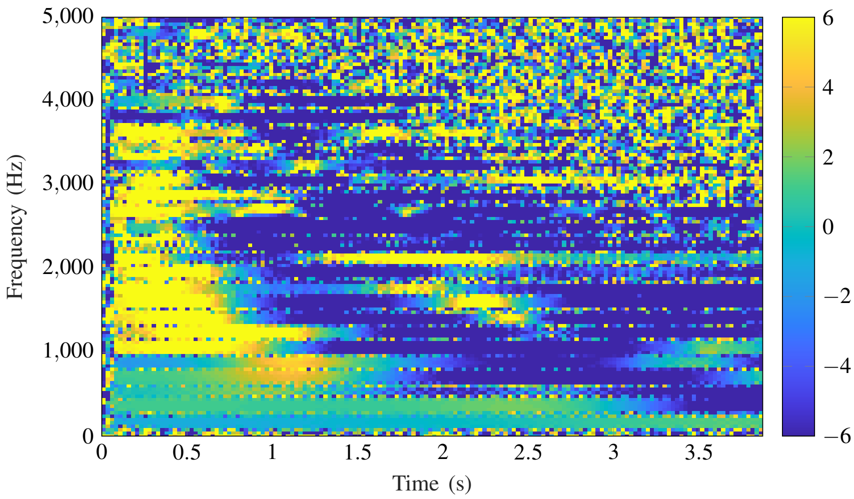

Figure 3. Difference in short-time power spectra (expressed in dB) for key 33 (F3) for both NP and UC playing conditions. Positive values (in shades of yellow) indicate higher amplitude for NP and negative values (in shades of blue) indicate higher amplitude for UC.

5 Hz (as it was by default in the Timbre Toolbox).

The LATs of all 88 keys are presented in Figure 5. A more negative number indicates a shorter attack time. While 51 of the NP tones have higher LAT, thus longer attack time, they are scattered across the whole range and the difference is not significant (mean LAT difference 0.044). No specific nor localised pattern is observed. When converted to seconds, these NP tones would have a mean difference of 2 ms and median difference of 0.6 ms respectively. On the other hand, in instances where the UC tones have higher LATs, the mean and median differences are 3 ms and 0.1 ms respectively. In essence, these differences are very small, suggesting that the attack phases for both tones are not dissimilar.

The temporal centroid is essentially the "centre of gravity" of the energy envelope in time and is defined in the Timbre Toolbox as:

$$\mathrm{TC} = \sum_{n=n_1}^{n=n_2} t_n e(t_n) \Big/ \sum_n e(t_n), \tag{2}$$

where n_1 and n_2 are the first and last values of n, respectively, chosen such that $e(t_n)$, the envelope signal, is

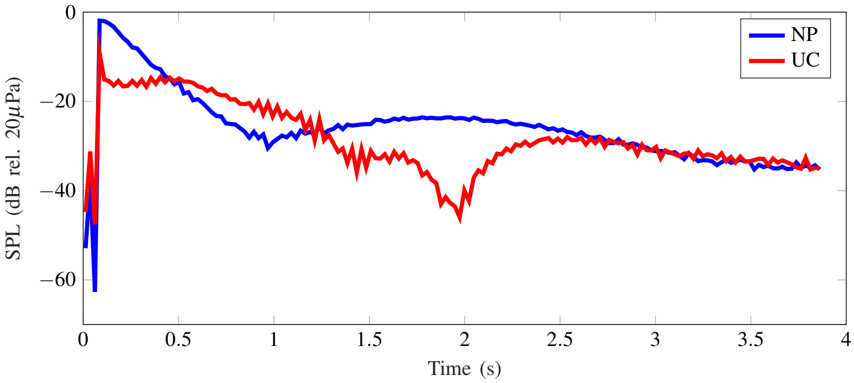

Figure 4. The sound pressure level of the 12th harmonic of key 33 (F3) plotted against time for two different playing conditions.

above 15% of its minimum value. Such treatment eliminates the inclusion of silent segments during computations. A low TC relates to a more "percussive" sound while a higher TC relates to a "sustained" tone.

The TCs of all 88 keys are shown in Figure 6. From the lower notes to the higher notes, TC decreases. This is because higher notes have faster decay and hence shorter duration, resulting in lower TC values. 34 of the NP tones have higher temporal centroid than UC tones. When the NP tone has a higher TC, it has a mean difference of 45 ms and a median difference of 18 ms. When UC tone has a higher TC value, the mean and median differences are 48 ms and 22 ms respectively. As the TC varies significantly more across the whole piano range, it is not known if these small deviations are perceptually relevant.

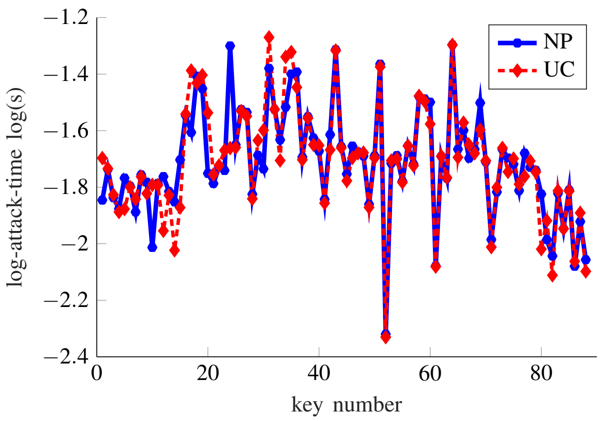

Figure 5. LAT of all keys for the two different playing conditions.

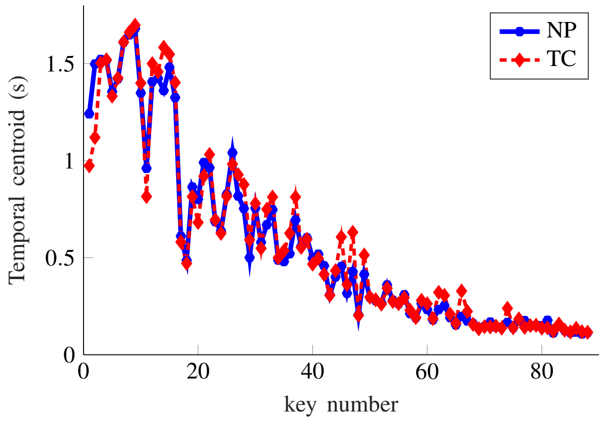

Figure 6. Temporal centroid of all keys for the two different playing conditions.

The normalised spectral centroid for key i, with fundamental frequency $f_{0,i}$, at time t_m is calculated as:

$$\mathrm{NSC}_i(t_m) = \sum_{k=1}^{K} f_k \cdot p_k(t_m) / \sum_{k=1}^{K} p_k(t_m) f_{0,i}, \tag{3}$$

where f_k and p_k are the frequencies and amplitudes as computed using an STFT centered on time t_m. The spectral centroids were first calculated using the Timbre Toolbox before they were divided by their own respective fundamental frequencies as estimated by YIN [6]. Figure 7 and 8 show the normalised spectral centroids of key 4 & 15 and key 18 & 33 respectively plotted against time. These four keys are specially selected to represent the four different stringing configurations as detailed in Table 1.

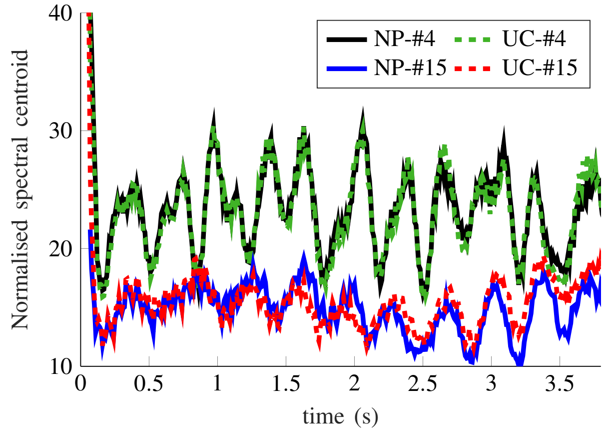

Figure 7. Comparison of the normalised spectral centroids between two different playing conditions for key 4 (C1) and 15 (B1).

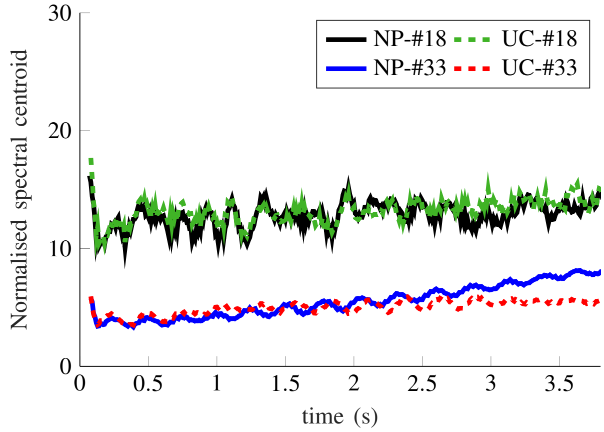

Figure 8. Comparison of the normalised spectral centroids between two different playing conditions for key 18 (D2) and 22 (F3).

Table 1. String configurations with respect to the key range.

Key range	Configuration
1 - 9	single string copper wound
10 - 16	double strings copper wound
17 - 20	triple strings copper wound
21 - 88	triple strings unwound

In both Figure 7 and 8, the evolution of spectral centroids of each key is similar when compared between the NP and UC tones. The maximum differences between playing conditions for these 4 keys are -2.1, -3.8, -2.1, +2.6 respectively, where a positive value indicates a larger value for the NP tone. The just noticeable difference (JND) of NSC was found to be around 0.11 for a trombone sound [9]. However, this result may not be directly applicable to the piano result. The average NSC of the trombone sound is around 3.25, which is markedly lower than the four piano notes shown (23.2, 14.9, 12.9 and 5.5). Furthermore, the NSC is calculated based only on the harmonics of the sound, instead of the full frequency spectrum.

Figure 9 shows the differences in NSC for all the keys plotted against time (vertical axis), showing differences up to ± 3 (positive indicates larger value in favour of NP tone). The red lines segregate the different stringing configurations as detailed in Table 1. The white zone indicates the noise region. It is computed by checking if its frame energy at that particular time step is below 1% relative to the maximum of each note. The frame energy is calculated in the frequency domain by the Timbre Toolbox to be the sum of all amplitudes squared in each window.

From key 1 to 9 where only one string is struck, no large difference of NSC is found. The small differences observed, e.g. at key 5 and 6, can be attributed to the softer part of the hammer that strikes the string when the UC pedal is used. From key 10 to 16 and 17 to 20, where the hammers strike two and three wound strings respectively, differences in NSC are more substantial, with a few keys showing higher NSC in NP or UC tones. From key 20 to 45 or so, where all notes have 3 unwound strings, NSCs are overall higher for NP tones, especially from 2 s onwards. From key 45 onwards, differences of NSC for the two tones are not large.

The pattern seen in Figure 9 could be influenced by the physical properties of the piano itself, such as the location of the termination points of the key at the soundboard. From key 1 to 28, all the notes terminate at the top one-third of the soundboard on the bridge. Meanwhile, for keys between 29 and 45, they terminate at the middle one-third of the soundboard. For the rest of the keys, they terminate at the bottom right of the soundboard. The lack of difference from key 45 onwards may be attributed to the presence of duplex stringing in the piano. From key 42 onwards, the rear duplex strings are no longer damped. The duplex strings are allowed to vibrate sympathetically and are perceptible [3]. What could have been in play is that even if the UC pedal is depressed, the effect from duplex strings in shaping the timbre dominate over the sympathetic leftmost string, so much so that no obvious changes of NSC is observed. To that end, further investigation in the actual physics of sympathetic vibration of a piano will be necessary before further insights can be derived.

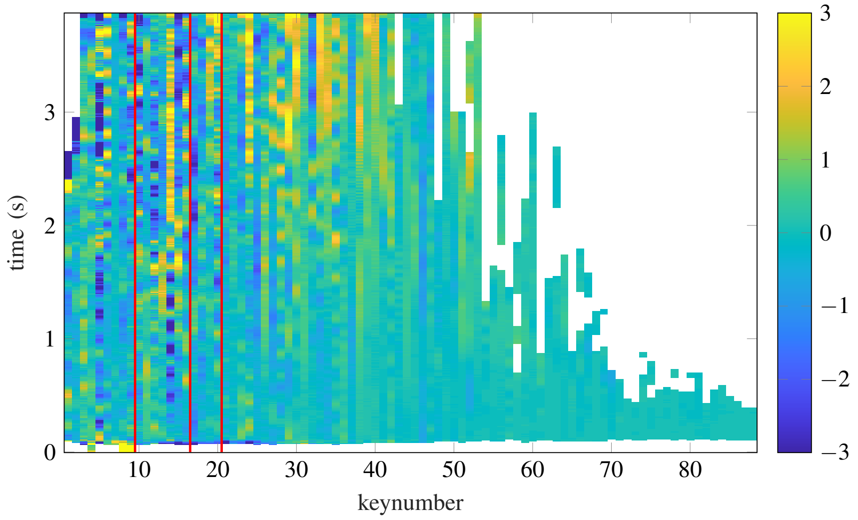

Figure 9. Difference of the normalised spectral centroids between two different playing conditions for all keys.

It is tempting to identify the discrepancies found between key 20 and 45 to be perceptually relevant. Carral's JND's for NSC is in the vicinity of 0.1 [9]. Even taking into consideration that the average NSC for all those keys are higher, at 6.9 and 6.7 for the NP and UC tones respectively, it is very plausible that the large observed differences, i.e. 2 or higher, are beyond the JND threshold. However, it must be reminded that the trombone sound in Carral's study is continuous with no decay while the biggest difference in NSC for the piano keys are found mostly in the decay section. These few variations between Carral's and current work will necessitate the extension of the present study. One obvious approach is to use the NP and UC tones in listening experiments in order to decide whether human listeners are able to distinguish these sounds.

4 CONCLUSIONS

To understand the differences in tone played without and with the *una corda* pedal depressed, the recordings of a piano, specifically the Ant. Petrof AP 275, for these two playing conditions are studied for all 88 keys. In the frequency spectrum, it is identified that the NP tone consistently has higher amplitudes in higher harmonics, particularly in the attack phase of the tone. Some of these harmonics become weaker than the UC tone in the decay phase. Psychoacoustically, only small differences are identified in two global descriptors, i.e. the log-attack-time and the temporal centroid. However, in the normalised spectral centroid, particularly for key numbers between 20 and 45 and in the decay region (after 2 s), large differences were identified but it is currently not known if these differences are perceptually relevant nor if they can be attributed to particular physical features of the piano. In order to answer these questions, further investigations, including listening test with the analyzed piano sounds, will be needed.

ACKNOWLEDGEMENTS

This research is funded by the EuroTech Postdoc programme and Marie-Skłodowska-Curie COFUND grant (agreement #754462). The recordings of the Petrof piano are jointly supplied by PETROF, spol. s r.o. and MODARTT S.A.S. The authors are grateful for all the support provided.

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