COMPARISON OF GRAND PIANOS ANT. PETROF AND MISTRAL

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Abstract: This paper describes the measurement of two Petrof grand pianos: Ant. Petrof and Mistral. The goal was to compare their parameters, i.e. harmonic spectra, decay time, relative sound level, spectral centroids, and cumulative line spectra (CLS). The complete range of 88 tones (keys) was measured in the anechoic chamber of Petrof, where we used a play-bench for precision. The obtained data were analysed and put into comparison. This analysis was supplemented by a comparison of selected samples (keys A2 and A4 played in forte and piano dynamics) to samples of three competing brands (Shigeru Kawai, Yamaha, Steinway).

Keywords: acoustic, anechoic chamber, Ant. Petrof, aliquots, bass, braces, cumulative line spectrum (CLS), decay time matrix, English mechanics, fast Fourier transform, grand piano, hammer velocity, harmonics, harmonic spectrum, keys, measurement, mid, Mistral, note, Petrof, play-bench, partials, relative sound level matrix, short time Fourier transform, spectral analysis, soundboard, periodogram, spectrogram, spectrum, string, spectral centroid matrix, Shigeru Kawai, Steinway, timbre, treble, vibration, voicing, Yamaha.

1. Introduction

The Petrof company is a well-known global manufacturer of concert grand pianos. The first of the two instruments that were measured comes from the more traditional product line. The P 284 Mistral (further referred to as Mistral) is their "masterpiece, the flagship of the PETROF brand" [3]. The manufacturer states that it "is beloved by musicians the world over, chiefly for its tremendous bass and resonant treble" [3]. It is a large concert instrument with a length of 284 cm, weight of 576 kg, and a large active surface area of the soundboard of 2,029 m^2. The other grand piano involved was the ANT. PETROF 275 (further referred to as Ant. Petrof), a flagship instrument representing the Ant. Petrof brand, a luxury brand of instruments that was presented to the public on the occasion of the company's 150th anniversary in 2014. It is 275 cm long and weighs 588 kg, the soundboard of the instrument is made of resonant spruce with an active area of 1,880 m^2. The company states that it "... was preceded by five years of development and two years of testing. This model brought numerous innovations to piano craftsmanship, with some actually having been patented "[3]. Thanks to a completely new and careful processing, it has "... a unique round tone" [3]. Both models are shown in figure 1.

If we compare the two instruments in gross mechanical parameters, we find that the material used for the production of the soundboards is identical (solid resonance spruce wood), as well as the one used for the bridges (solid resonance spruce wood).

The Ant. Petrof has a beech instrument frame, while the frame of the Mistral is made of twelve beech and birch slats. We also find a difference in the material from which the peg is made, in the case of the Ant. Petrof it is made of Canadian Maple, while in the case of the Mistral it is made of plywood. Both instruments have a soundboards reinforced with sixteen ribs. The divisions of the strings between the bass and treble bridges is also different. The Ant. Petrof includes 20 bass strings and the Mistral 18. The number of strings is also different, 21 for the Ant. Petrof and 18 for the Mistral brand. The divisions of the strings into choirs is the same for both instruments. With its length of 284 cm, the Mistral is almost 10 cm longer than the Ant. Petrof, however, is lighter by 12 kg and stands out with a larger active resonance plate area by 2,029 m^2.

As part of the construction of the string covering, the so-called aliquots are used for the

Figure 1. Grand pianos Ant. Petrof and Mistral

treble tones of both grand pianos. The Ant. Petrof contains front aliquots for tones D5 to C8 and rear aliquots for tones D4 to C8. The ratio of the length of all aliquots with respect to the mensuration lengths of the respective strings is identical for both instruments. However, the rear aliquots on the Mistral extend to a sharp compared to D4 in the Ant. Petrof.

2. Constructional peculiarities of grand pianos

2. 1. Piano action

Modern instruments generally use the so-called action equipped with a repetitive mechanism. During the development of the piano, this type of action has proven to be more reliable, allowing artists to play with significantly greater expressivity (dynamic range) compared to the competing Vieniesse action. An important feature of the piano action is the repetitive mechanism, which allows the same note to be repeated in rapid succession. The speed and smoothness of the entire piano action determine how "lively and agile" is the instrument perceived, and it is one of the aspects that players evaluate along with the relative balance of the keys, perceived depth of keystroke (distance from the default key position), and the finish of the key which adds to the feel of playing the instrument.

Piano key as a gyrator: converting speed into force

From the physics standpoint, the player uses the piano key as a gyrator: the speed of the keystroke is converted to the force with which the hammer strikes the string. The way this conversion is implemented determines the dynamic range of the instrument. For example, „on a Steinway grand piano, Dijksterhuis (1965) measured T_s= 12 ms for a strong touch to T_s = 140 ms for a soft touch; the ratio is 11.7, which gives a dynamic range of 21 dB in the force. Substituting a light plastic key (about 50 g) for a wooden key (about 130 g) reduces the apparent mass at the touch point by about 10% and thus increases the velocity V_0 by about 5% for the same force F" [2]. See Figure 2.

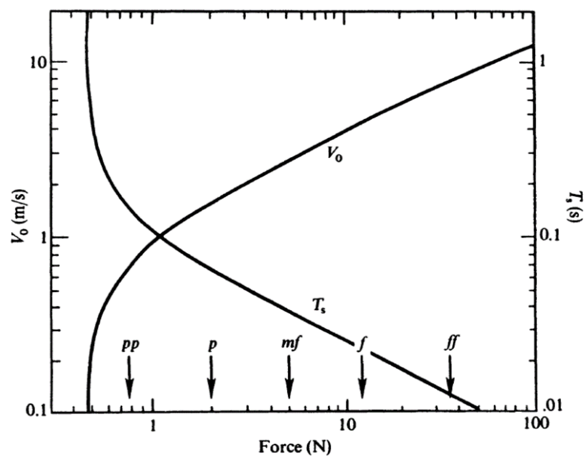


Figure 2. Hammer velocity (V_0) and key depressing time (T_S) for different values of force (assumed to be constant during the time T_S) [2]

The timing of the keystroke is one of the key elements when creating chordal timbres. If, for example, we were to strike the three notes of a simple triad exactly at the same time, there would be a strong masking of the notes resulting in creation of almost "unified" voice ratios.

Note: This can be easily demonstrated when using virtual instruments by programming the notes to be played in a uniform way in timing as well as level.

Piano players work with the strength of individual voices (i.e. the speed of keystroke) only to a certain point. Most of the work when differentiating chordal voices is done by slight adjustments in timing. "A skilled pianist could play a chord in such a way that a melody note sounds earlier or later (but at the same intensity) as the rest of the chord. Henderson (1936) contends that, contrary to general opinion, accentuated notes are not played with greater intensity than unaccentuated notes; rather, the pianist is inclined to play the accentuated notes a little earlier. Vernon (1936) remarks that Padarewski played 56% of the chords asynchronously in Beethoven's Moonlight Sonata but only 20% in Chopin's Polonaise Militaire. The touch of a pianist appears to be of importance in piano performance."[2] The speed of the pressing and the speed of the returning of the hammer to its original position are therefore essential parameters affecting the playing technique.

2. 3. The soundboard

Resonance of the piano is greatly affected by the entire resonance box which includes the soundboard that is reinforced by ribs and on which the bridge is glued. The soundboard completes the tone generated by the string. It has its own natural frequencies, also called modes, thus it does not amplify all the frequencies generated by the string equally. When the soundboard is further stiffened by attaching a cast-iron frame and fitting it into the body of the instrument, the natural frequencies of the resonator modes will raise even more. Resulting formant regions amplify a wider frequency range compared to a bare soundboard that has not been, impedance-unloaded plate. However, the resulting position of the formants does not depend only on the stiffness of the entire system and the soundboard dimensions. The structure of the wood as such can also show to some extent. This brings to the game a certain level of uniqueness that can never be accurately estimated.

Determining the degree to which the modes of the soundboard are reflected in the resulting sound of the instrument is not an easy task due to the variable location of the excitation force caused by the distribution of the strings along the entire length of the bridge and the large range of the frequencies the strings produce. Therefore, it is first necessary to determine the natural frequencies of the entire assembled resonator (including the tensioned strings), then to determine location of the nodal and antinodal lines for each of them, and finally to compare the location of these nodal and antinodal lines and their corresponding modes with the position of the strings alongside the bridge and the fundamental frequencies and higher harmonics they produce.

An important phenomenon occurs during the transfer of energy between the oscillator and the resonator. If the mechanical impedance of the string and the board are appropriately matched at the point where the energy is transferred, all the energy of the string is quickly radiated by the soundboard, producing a loud tone. However, given that there is a limited amount of energy in the system, it is clear that the loud tone will also be short and thus lack a certain sustain and "singing quality". When designing an instrument with known frequency dependence of the mechanical impedance of the resonator (for example, based on modal analysis using the finite element method), the result is always a compromise between a short and loud tone and a quieter, longer and more "singing" one.

2. 4. Number of strings, their tuning and voicing

The heart of the piano are the strings. They convert part of the kinetic energy of the moving hammers into vibrational energy, which operates in different modes of vibrations and is transmitted to the bridge and then to the soundboard. The means of this conversion affect the sound quality of the instrument. When the hammer strikes the string, the reflected impulses return from both ends of the string and interact with the hammer in a complicated manner in a short time. After the hammer has left the string, the string vibrates freely and in a less complicated (more harmonic) manner.

The steel wire with high strength is used for piano strings. But the highest possible string tension with the minimization of in-harmonicity is also required. „This results in tensile stresses of around 1000 N /mm^2, which is 30-60% of the yield strength of high strength steel wire. For steel with an elastic modulus of 2 x 1011 N /m^2, this results in an elongation of about $\frac{1}{2}$% when the string is under tension."[2] The treble strings of the piano are made of solid wire, the lower strings, on the other hand, consist of a solid core wrapped with one or two layers of wire (usually copper). This wrapping minimises stiffness (and thus inharmonicity) in the lower strings where more mass is needed. The diameter of the copper overwrap can vary from twice (the lowest string) to one quarter (the highest wound string) of the diameter of the core. An important decision that every designer must make at the very beginning of the design process is the division of the strings into bass and treble - that is, which strings to place on the main bridge and which on the bass bridge.

Three types of string combinations, so-called string choirs, are used on both the grand pianos: one, two, and three choirs. The points of transition between the types of choirs play an important role in timbral refractions. The tuning or slight detuning of the choirs is then related to the length of the tone and the timbral processes (so-called breathing) that take place during the decay of the tone due to the phase difference of the standing waves of each string in the choir. Beats (frequency interferences) are thus created. They are desirable to a certain degree, because they can enrich the timbral development of the tone. The tuning and so-called voicing of the piano plays a crucial role in the final sound. The piano tuner, both tunes and voices the piano - unifies timbres. In addition, tuning does not take place according to equal temperament (e.g. octave 2:1), but more complex principles come to play involving psychoacoustics principles, i.e. subjective tone height.

Note: Psychoacoustic parameters and quantities were determined by research and testing of listening panels and described in the works by Erbehard Zwicker [1] (Die Münchener Schule der Psychoakustik) and later taken over by Alois Melka [7] from AMU. In the area of pitches, you can work with the mel unit and the so-called mel scale, which express the sensitivity of the human ear to tuning in different frequency bands (the higher in the spectrum, the less sensitive the human ear is to distinguishing pitch differences).

Piano tuners spread the octaves, and the human ear finds these slight shifts in the fundamental frequency more pleasant than exact tuning ratios. In addition, the tuner/intoner works with the already mentioned slight detuning of the string choirs and also with softening the hammer (needling - i.e. increasing the contact time) or hardening the hammer (shortening the contact time and increasing the force), which can then generate a wider or narrower spectrum. Both measured grand pianos were therefore left in an anechoic room for several days in advance to acclimate to the room temperature and were then tuned and voiced according to the manufacturer's standards and kept in this condition for as long as possible during the measurement.

3. Measurement: room, technical equipment, measurement methodology

The samples were measured in the anechoic chamber of Petrof, Ltd. in Hradec Kralove (see Figure 5). „The inner parts of the anechoic chamber consist of a ferroconcrete monolith, whose walls are 30 cm thick. The monolith is mounted on springs and its weight including 4,180 absorptive wedges fluctuates around 300 tones. As it lies on flexible suspension, the resonance frequency of the chamber is approximately 5,5 Hz."[3] For the playing of individual tones with a certain dynamic, a "playbench" [12] made by VÚTS, a.s. was used, with an adjustable force of pressing the key and the duration of its pressing (see Figure 3). Unlike a live player, this playing mechanism is always able to play all the notes with the same force, so there is no influence of the measurement by the human factor.

Figure 3. The play-bench [12] made by VÚTS, a.s.

The mechanical finger is finished with a tip made of silicone and teflon tape to eliminate noise when touching the key (see Figure 4). The white and black keys were measured separately.

Figure 4. Mechanical fingers

For measuring of the Ant. Petrof samples (measurement took place on 23/11/2017) for subsequent spectral analysis, a DBX RTA-M measuring microphone with a omnidirectional characteristic was used. The microphone was placed 145 cm from the centre of the cast iron frame at a height of 130 cm from the level on which the piano stood. This microphone location was chosen based on the expected directional radiation of the instrument as well as the common location of the potential listener. The microphone was connected directly to the preamplifier of the RME Babyface Pro sound card. The second measurement of the Mistral took place on January 25, 2018. Sound samples for spectral analysis were recorded with the same microphone as during the first measurement. However, for technical reasons, a different sound card (Presonus Audiobox 1818VSL) was used during this measurement.

Figure 5. The anechoic chamber of Petrof

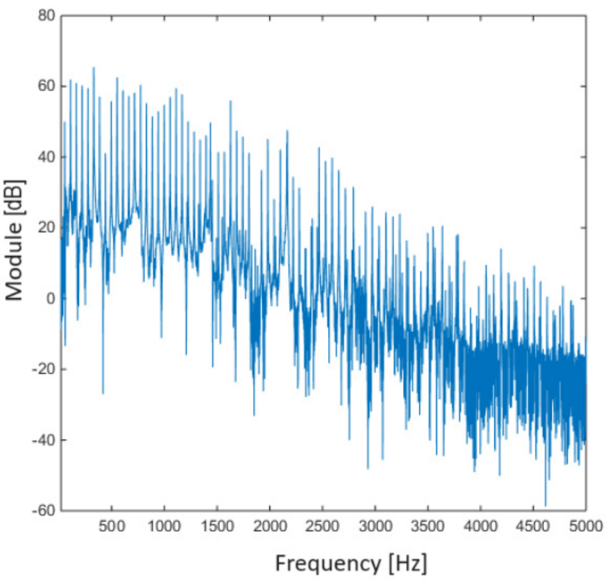
Due to noise limitations, we had to use a different mic preamplifier gain setting and the common level ratio was done by calibration estimation. That is why we do not compare samples acquired during these two measurement sessions with each other in relation to their acoustic power. The samples were recorded in DAW Cubase 5 using a sample rate of 48 kHz and a bit depth of 24 bits.

4. Measured parameters and their calculation methods

First, the so-called dynamic envelope was analysed from the recorded samples. Typically, a two-dimensional dynamic envelope curve can be specified at different resolutions depending on the time window. From it, we identify not only how loud the tone is when it begins in the attack phase, but also how it will develop over time.

Note: It is desirable to harmonise the string choirs in such a way that the tone lingers for a long time and, by reaching the correct beats during the decay section, breathes - getting into clashes/subtraction and synergy/summation of the positive and negative amplitudes of the sub-waves contained in the main composite wave.

Two types of graphs are essential for timbral analysis: the periodogram and the spectrogram. We will display both using the so-called Fourier transform. Using it, we obtain the so-called module frequency characteristic of the tone.



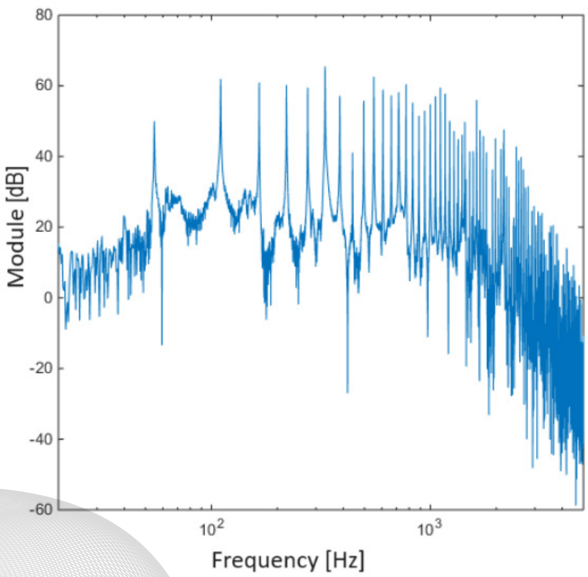


Figure 6. The periodogram

The key parameter for the appropriate setting of this display is the length of the window and with it the associated number of samples from which the Fourier transform is calculated. The frequency resolution in the spectral domain will thus correspond to the frequency calculated from the relation:

$$f = \frac{f_{vz}}{N} \; [\mathrm{Hz}]$$

where f_{vz} is the sampling frequency and N is the number of samples from which the Fourier transform is calculated. Time difference then logically corresponds to the following formula:

$$t = N\frac{1}{f_{vz}} \quad [\mathrm{s}]$$

If we add a timeline (x-axis), we create a spectrogram that allows us to monitor the spectral power density over a longer period of time.

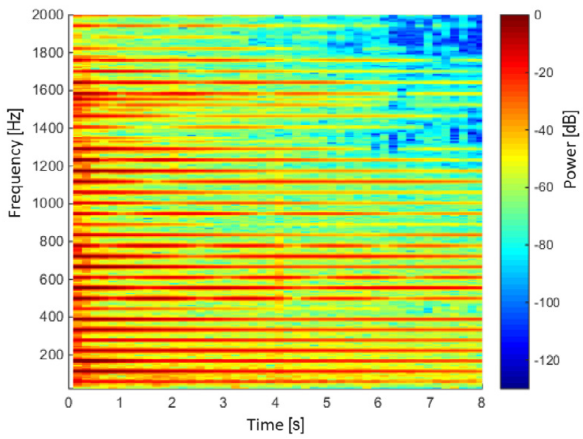


Figure 7. The spectrogram

One of the extended additional methods in connection with the Fourier transform describing the character of the spectrum is the so-called spectral centroid. Its value expresses the frequency position of the energy centroid of the spectrum, which can be calculated by the relation:

$$SpC = \frac{\sum_{k=1}^{N} f(k)c(k)}{\sum_{k=1}^{N} c(k)}$$

where c(k) denotes the intensity of the spectral coefficients and f (k) their mean frequen-

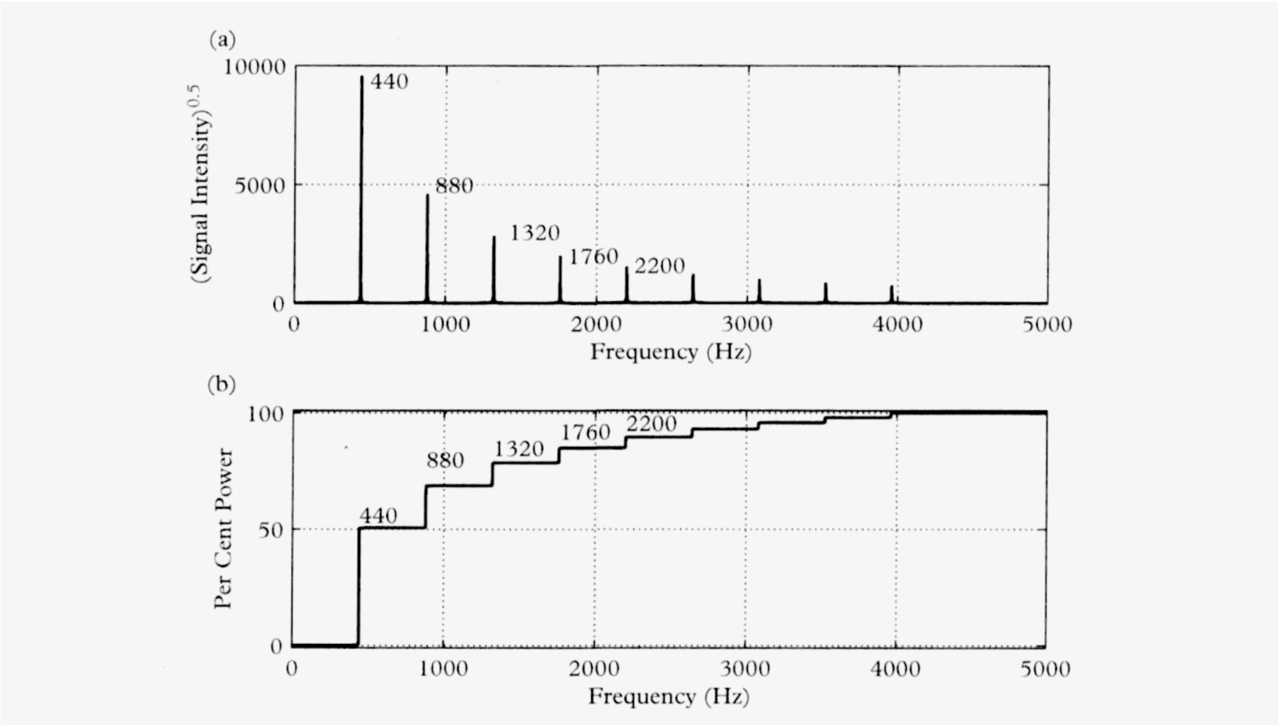


Figure 8. Line spectrum and cumulative line spectrum [6]

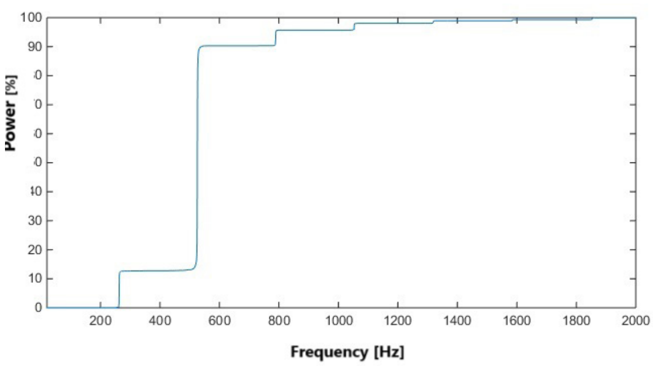
cy. The graph of the spectral centroids makes it clear and reveals whether the energy of the spectra of 88 tones holds together a balanced linear or exponential curve, whether some tones do not stand out significantly from the line, i.e. they are significantly poorer in the number of harmonics c or excessively rich.

For a clearer description of the power distribution with respect to the frequency of harmonics was used the cumulative line spectrum (CSL), which "is a running sum of the line spectrum." [6] See Fig. 8, where „the x-axis contains frequencies in Hz. The y-axis gives the accumulated power in percent." [6]

The method works with parameters „...sample times t, sample values y(t), ...frequencies (Hz), ...intensities $[A(f)]^2$, ...accumulators S, ... normalized accumulators $\bar{\bar{S}}$." [6] The formula is essential:

$$S_{(k)} = S_{(k-1)} + [A_{(k)}]^2$$

By the calculation, we can obtain "accumulated power at each frequency S_k"[6], that is "all of available signal power has been accumulated and sums can be scaled" [6]. Using this type of analysis, we can easily compare the power distribution between individual frequencies, a range of frequencies, or tones too. And that is for example in a 3D view.



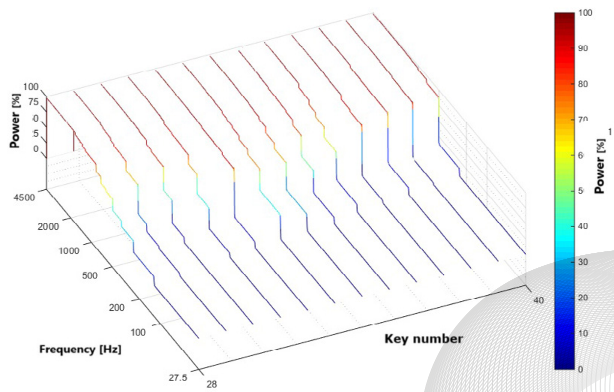


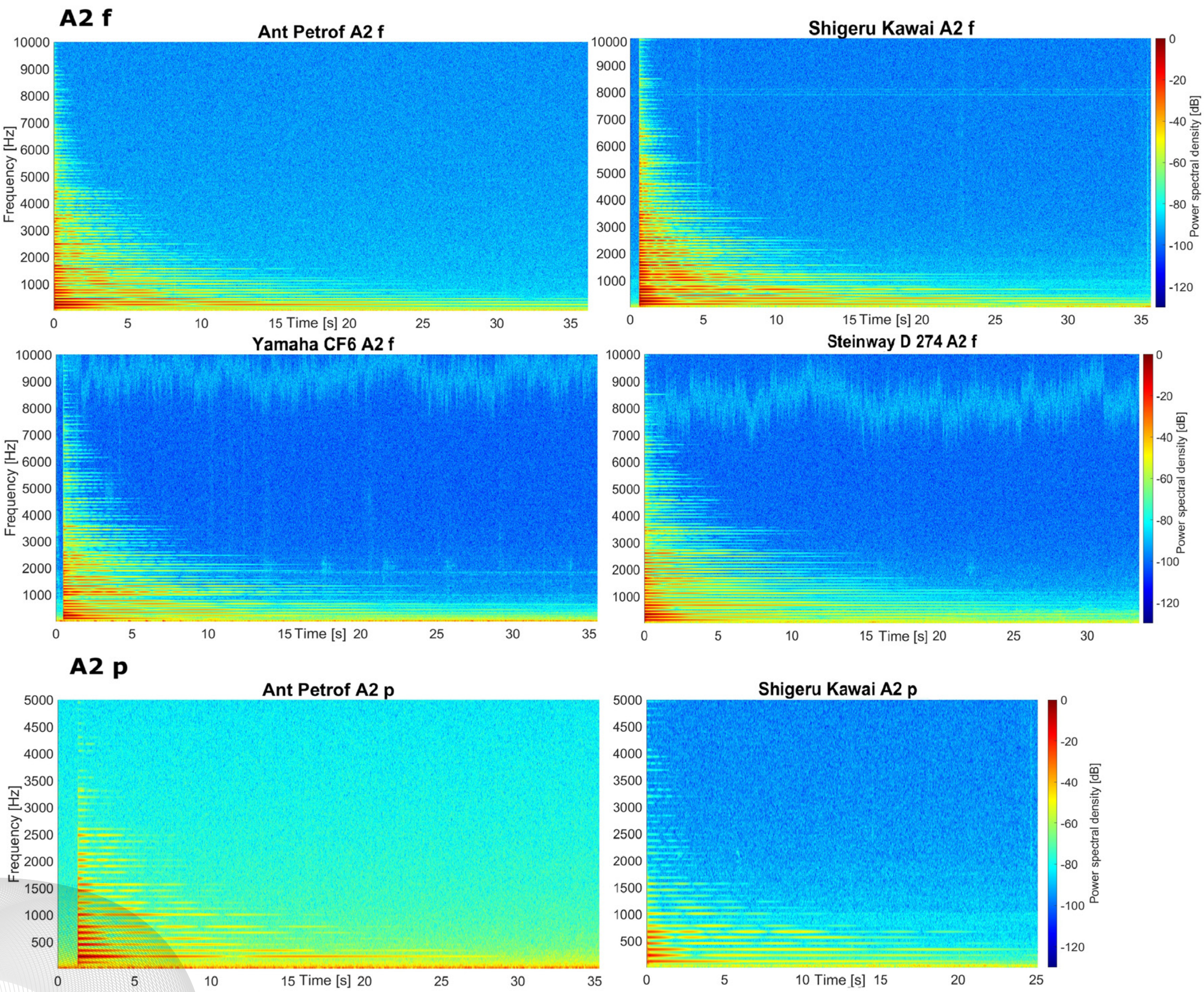
Figure 9. Cumulative Line Spectrum (CLS)

Note: The mentioned types of analyses can be supplemented with other methods such as the spectral spread, spectral skewness, spectral kurtosis, spectral flatness. By summarising them, one can further specify the quality of the individual spectra, their difference from each other and potential deviation from the desired ideal sound.

5. Comparison of selected tones with other brands

In the analysis, not only Petrof grand pianos were compared, i.e. Mistral and Ant. Petrof, but also the grand piano spectrum of Ant. Petrof and other brands: Shigeru Kawai EX-278 (Studio Na Orlí, Brno), Yamaha CF6, (JAMU chamber hall, Brno), Steinway D-274 (JAMU concert hall, Brno). Tones within all octaves were selected, but for the sake of demonstration we only present a selection of two samples: A2 in *piano (p)* and *forte (p)* dynamics and A4 also in piano and forte dynamics. The analysis is carried out using spectrograms, their time display on the x-axis is adapted to the duration of the tone and the range of the spectrum on the y-axis remains constant with limit set to 10 kHz.

Measured samples in order from left to right down and again from left to right: great A (A2) in forte dynamics: Ant. Petrof, Shigeru Kawai, Yamaha CF6, Steinway D-274, great A (A2) in piano dynamics: Ant. Petrof, Shigeru Kawai, Yamaha, Steinway D-274.



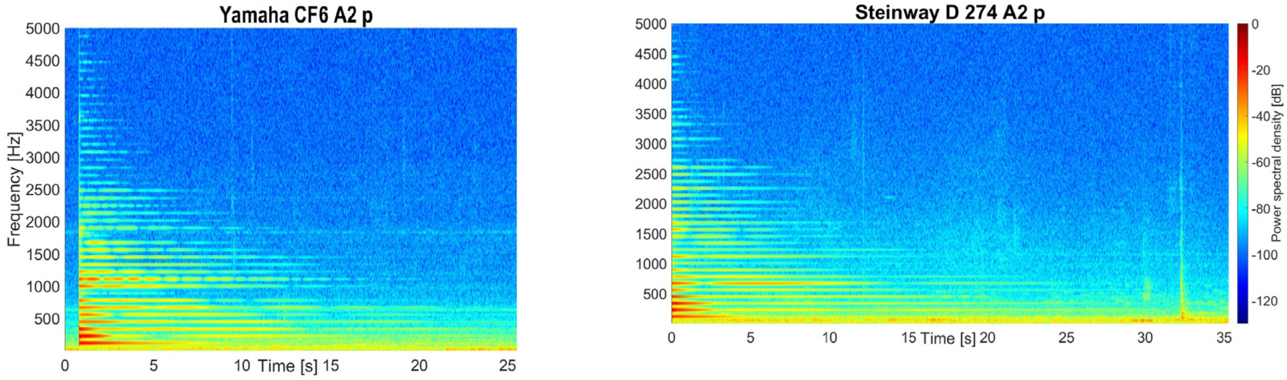


Figure 10. Comparison of tone A2 in dynamics f and p

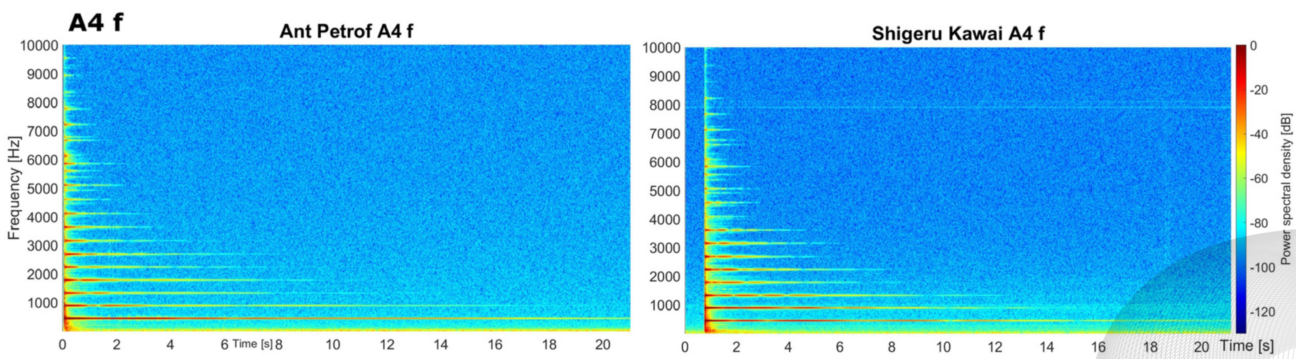
When the tone A2 is played in piano dynamics, usually soft timbres are required: Kawai has the narrowest spectrum from all with the strongly breathing and changing amplitudes of partials during decay. Yamaha and Steinway with no so soft spectra keep the timbre more uniform in time, not so breathing (see last for spectrograms in Figure 10 showing *p* dynamics *piano)*. In contrast with samples, Ant. Petrof of the other brands shows the spectrum too wide for dynamics in piano. The timbre of the Ant. Petrof grand piano in *p* comes out as the most saturated from all, in the attack phase it contains a large, strongly continuous (and therefore ringing) spectrum and further counts 25-30 components (partials) gradually fading. The so-called cluster band of higher harmonics is also present functions within this timbre, causing a the higher roughness and sharpness of the tone.

Note: The methodology used in this article when classifying the quality of the spectrum is based on work of Václav Syrový [11] (the band 1-8 components sound as intervals, the band 9-16 sounds chordal, the band 17-33 sounds cluster-like and the band 34-66 components sounds like quasi-noise).

Not only in the case of grand pianos, but also upright pianos, a soft timbre in low dynamics is desirable (so it is not only a wide dynamic range of the instrument, but also its wide timbre range).

The tone A2 in the forte dynamics: the spectrum range in case of the Kawai, Yamaha and Steinway grand pianos expands, their cluster and quasi-noise bands increase. The tone becomes especially more ringing and most contrasted in case of Kawai and Steinway (and that is desirable in the lower octaves in *f* dynamics). The tone A2 in forte played by the grand piano Ant. Petrof did not however bring any major new timbre opposite its dynamics *p*. The timbre range here is flatter (see first four spectrograms in Figure 10 showing *f* dynamics).

The measured samples in order from left to right down and again from left to right: one-line a (A4) in forte dynamics: Ant. Petrof, Shigeru Kawai, Yamaha CF6, Steinway D-274, one-line a (A4) in piano dynamics: Ant. Petrof, Shigeru Kawai, Yamaha CF6, Steinway D-274.



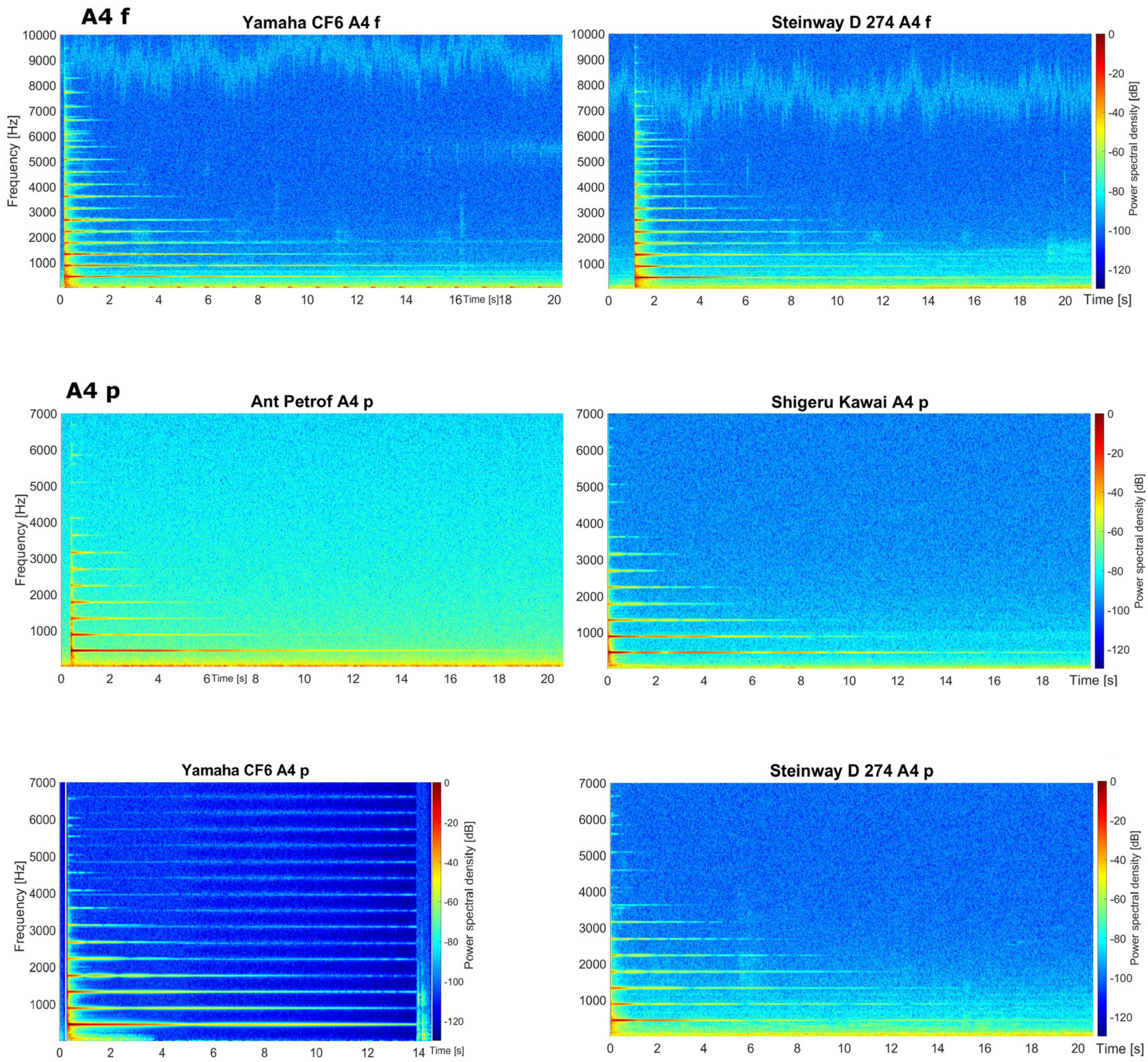


Figure 11. Comparison of tone A4 (one-line A) in dynamics f and p

In the case of the piano one-line octave in which a large part of the melodies is exposed, the number of partials is usually much lower and narrower compared to the great octave. Even here, however, a wide dynamic and timbral range is required. Ant. Petrof shows the biggest and the best timbral contrast (between dynamics *p* and *f*), but its tone quickly ends. Its timbral range is clearly different from the competing brands such as Kawai and Steinway with not so divergent spectra between *f* and *p*. The timbral range in case of the Yamaha grand piano is even narrower. Both Petrof and Kawai show strong phantom components in the spectrum near the 10th to 13th/14th of partials causing inharmonic admixtures in an otherwise harmonious timbre. On the contrary, the Yamaha and Steinway spectra are more homogeneous and clean in terms of harmonic ratios, and thus also harmonic timbres. See Figure 11.

6. Comparison of pianos Ant. Petrof and Mistral

Let's move on to the analysis of the grand pianos Mistral and Ant. Petrof. We will deal with matrices comparing the decay envelopes, the performance of all 88 tones in five dynamics, matrices comparing the spectral centroid and the cumulative line spectrum.

6. 1. Decay time matrix

In case of a matrix comparing dynamic envelopes (there is no significant sustain phase in them), one type of values is important: the process in the decay phase.

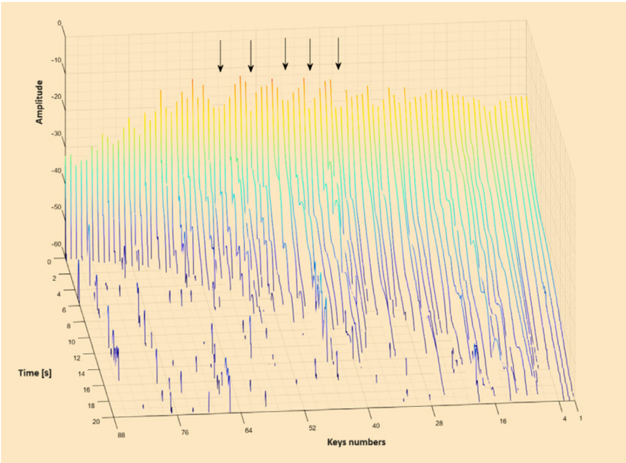


Figure 12. Decay time matrix of Ant. Petrof

In the Ant. Petrof grand piano, inconsistencies in volume were identified in the attack phase: decrease on keys 28-30 (from C3 to C#3), on keys 37-38 (from A3 to B3), on keys 44-47 (from E4 to G4) and from key 58 to key 61 (from G5 to A#5). The dynamic difference is in the range of 4-8 dB. Analogically, the decay phase is also shortened for these tones starting at low dynamics, in the range of approx. 2 to 4 seconds. See Figure 12.

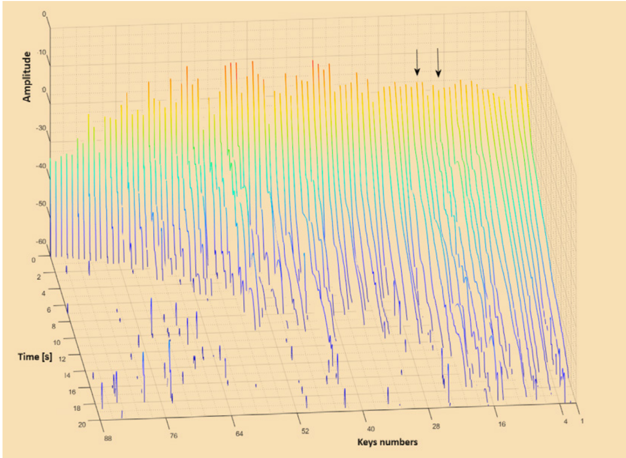


Figure 13. Decay time matrix of Mistral

The Mistral grand piano matrix contains the following differences in the envelope: volume inconsistencies in the attack phase: decay on keys 32-36 (from E3 to G#3), decay on keys 46-19 (from F#4 to A4) and decay in the range of keys 58-61 (from F#5 to A5), up to 15-16 dB. Here, the tones in the decay phases surprisingly maintain a more or less balanced exponential decay. See Figure 13.

6. 2. Relative sound level matrix

Samples played in five different dynamic levels were analysed and loaded into the sound level matrix: *pp, p, mf, f,* and *ff*. We will focus again on the consistency and fluidity of the curves and their overall outline.

Figure 14. Relative sound level matrix of Ant. Petrof

In the case of the Ant. Petrof brand, the shift in the dynamic level compared to the "neighbouring" notes appears prominently on key 29 (C#3) prominently on key 36 (G#3), moderately on key 42 (D4) and prominently on key 53 (C#5). However, the difference is a maximum of 3 dB in the *ff* and *f* levels, and a greater 7 to 9 dB in the *mf* level. See Figure 14.

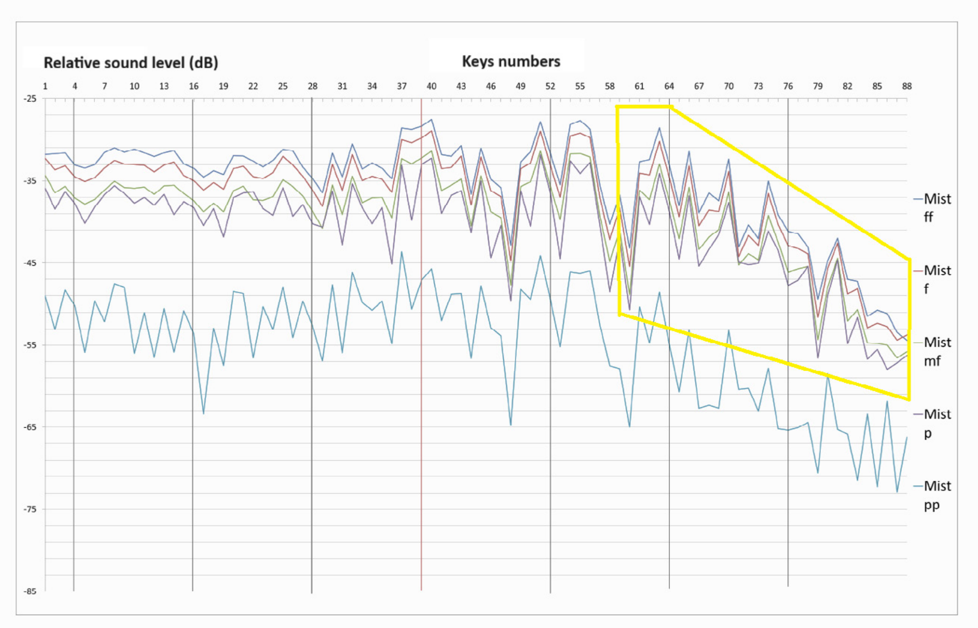


Figure 15. Relative sound level matrix of Mistral

In the case of the Mistral grand piano, the shifts in the relative sound level are evident on key 36 (G#3), very clearly on key 47 (G4) and very clearly in the range of keys from 58 to 61 (F#5-A5), compared to the neighbouring notes up to a range of 15 dB. Moreover, in the case of the Mistral, the curves in the *mf-ff* dynamic levels approach each other significantly but identically in parallel. I.e., the instrument here does not have a significant dynamic range, but performs similarly for each key (and pianists will probably appreciate this as a dynamic constant). See Figure 15.

6. 3. Matrix of spectral centroid

The data for the calculation of the spectral centroid was also generated from the five dynamic levels mentioned above. The curve shows the position of the spectral centroid with respect to the fundamental frequency of the tone (Y-axis).

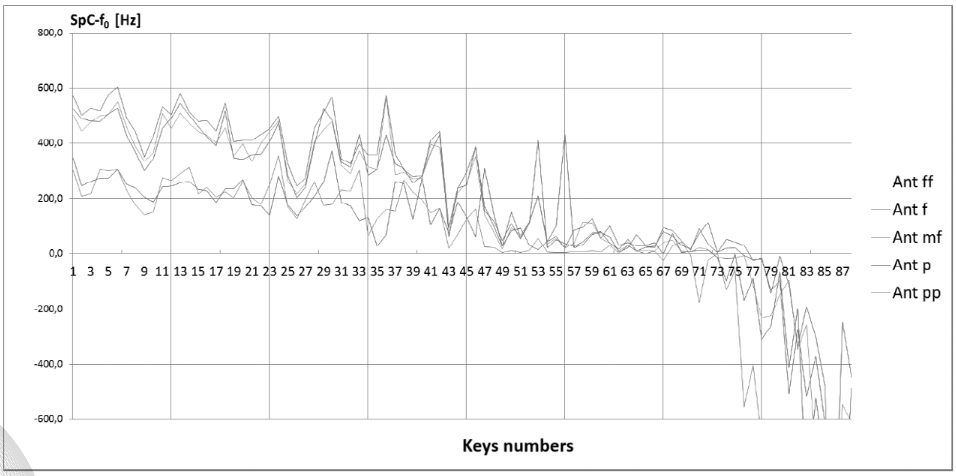


Figure 16. Matrix of spectral centroid of Ant. Petrof

Shifts in the lines of spectral centroids of the Ant. Petrof grand piano can be found on keys 25-28 (from A2 to C3), on key 43 (D#5) and in the range of keys 49-51 (A4-H4). See Figure 16.

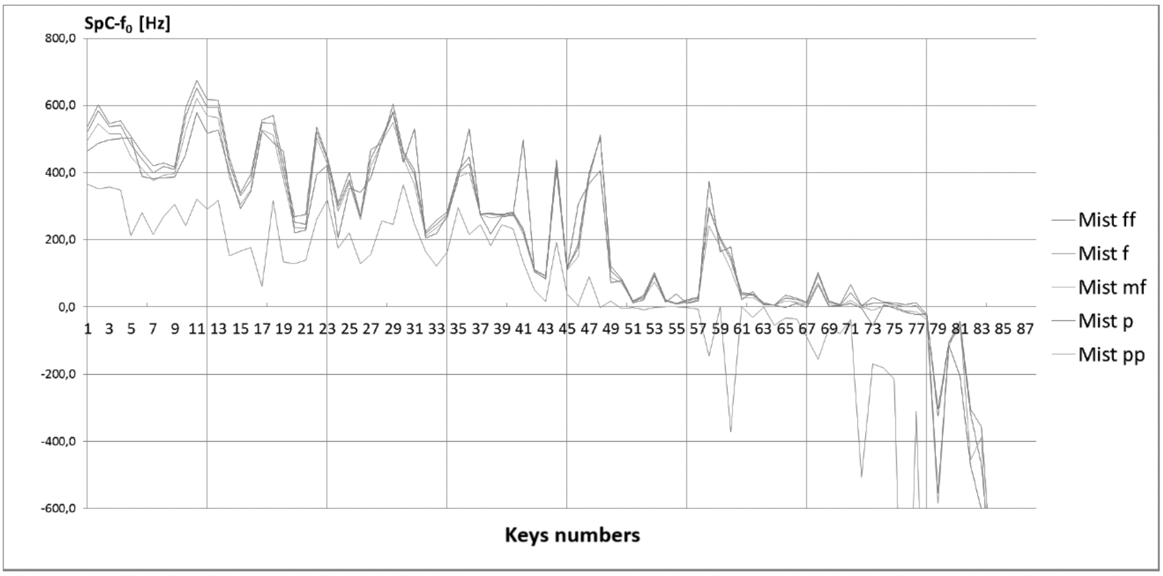


*Figure 17. Matrix of spectral centroid of Mistra*l

Shifts in the curve movement of the spectral centroid in the case of the Mistral brand are also significant. We identified them on keys 16-17 (C2-C#2), 19-21 (D#2-F2), 32-34 (E3-F#3) and in the band from keys 50 to 57 (F4-C5). Here, the spectral centroid sometimes even "floats" up to an octave and a half. As was the case with power, when it comes to the Mistral brand, in the case of the Mistral brand, the spectral centroid curves converge in the *mf-ff* dynamic levels. See Figure 17.

6. 4. Cumulative line spectrum: CLS

The analysis of the so-called cumulative line spectrum informs about the power of the individual frequency bands and shows how the final energy is gradually composed/accumulated in the entire spectrum. The method is a suitable complement to the spectral centroid. The analysis was performed from samples of *f* dynamics.

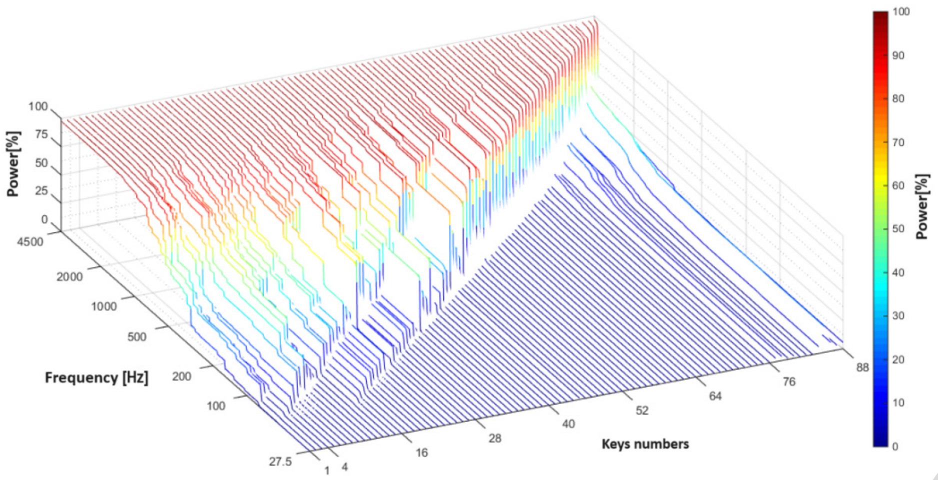


Figure 18. CSL of Ant. Petrof

In the overall comparison of all tones in the 3D view, we discover the type of power increase in the matrices of both instruments. In the case of both instruments, the absence of energy in the fundamental is clearly visible in the deepest thirteen notes (from A0 to E2). See Figure 18.

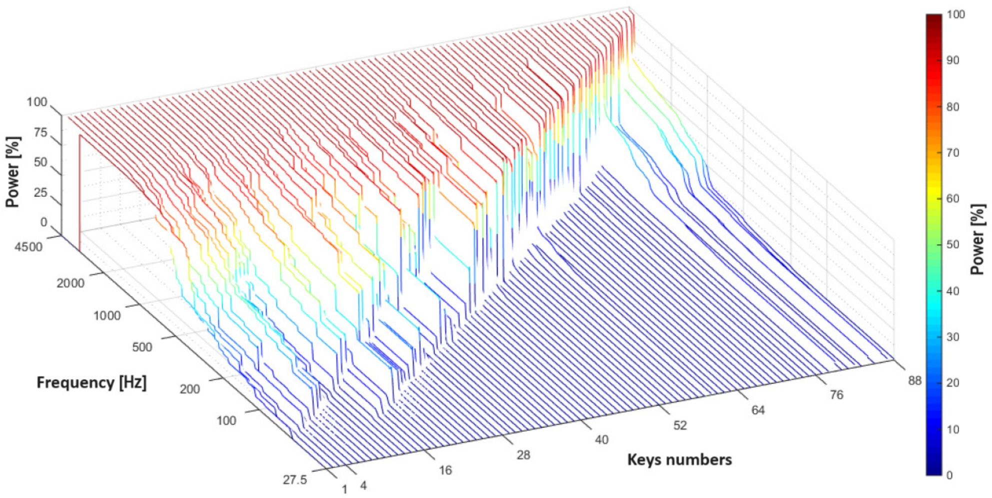


Figure 19. CLS of Mistral

This phenomenon is often associated with the 1st resonator mode, which is found in instruments of this size in the 55-70 Hz range. According to theoretical assumptions, the fundamental frequency begins to have an observable amount of energy at the 13th key with a fundamental frequency of 55 Hz, which corresponds to the actual measurement. Furthermore, there is a noticeable tendency in the changing of the energy distribution towards the fundamental frequency as the number of the key increases. In the four-line octave, we notice a clear amount of energy lying below the fundamental level, which corresponds to the energy of the noises that also arise during playing. See Figure 19.

7. Discussion

All 88 tones of the Mistral grand piano and the Ant. Petrof grand pianos were compared and in the case of power and spectral centroid centroid, the analysis was performed in five dynamics *pp, p, mf, f, ff.* The large gap between the *p* and *pp* (on the y-axis) curves for both the performance and spectral centroids is debatable, for both types of piano. It probably occurs due to the imperfect distribution between the different settings of the playbench which do not correspond to the actual dynamic levels (on *pp* is the weight of the artificial finger probably set too light). The solution would probably be adjusting the playing force by changing the weight.

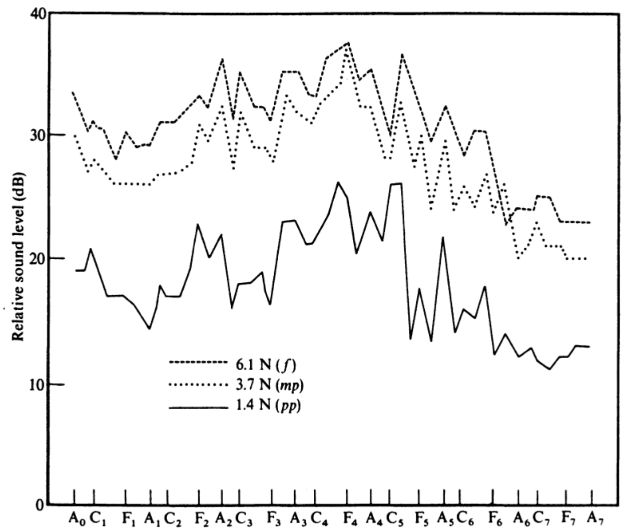


Figure 20. Sound levels for all 88 notes on an upright piano with different playing forces (Lieber, 1979) [2]

On the other hand, other measurements, e.g. upright pianos, show a similarly larger difference between sound levels in *pp* and *mp* dynamics corresponding to the excitating forces N, and a smaller difference between sound levels in *mp* and *f* dynamics (see Figure 20). The issue should be compared for more measurements and more types of pianos.

In the relative sound level matrices as well as in the spectral centroid matrices, we often come across significant inconsistencies and shifts on the curves. In case of the dynamic level, they begin at about the 29th key (C2 in the great octave) and end at around the 76th key (starting with C7 in the four-line octave). In the case of the Mistral, twice on key 47 (G4) and in the band from 58th to 61st keys (F#5-A5), the difference exceeds 15 dB, i.e. out of the tolerance of one dynamic band. These inconsistencies occur in the treble region (descant) on the triple choir, i.e. outside the transition from one string to a double choir or from a double choir to a triple choir. The probable explanation will be the different voicing (preparation) of the softness or hardness of the hammer, including its internal structure. In the case of the curves of the spectral centroids, the shifts are even larger and are present accross the entire keyboard. Here, too, the voicing of the hammers most likely plays a major role. It is also true that the timbre of tone becomes more unified when the lid is narrowly positioned (but not covered).

When During the comparison with the competing brands, only two tones were selected, A2 and A4 recorded on the same recording device with the same input sensitivity and the same position (above the top rail to the right of the pianist) of the same microphone, but in different acoustic environments with different room modes and reverberation. Even so, the samples provided sufficient quality for comparing the spectra, their harmonic and non-harmonic components. Of course, a complete analysis of all 88 keys at different dynamics in an anechoic room would be even more accurate and objective. It would be useful to supplement the current parameters of the analysis with others, which can be, for example, the degree of inharmonicity in percents or cents and psychoacoustic units such as sharpness, roughness, lightness, fluctuation strength, subjective duration, nonlinear distortion, etc.

8. Conclusion: measured values and characteristics of both Petrof grand pianos

8. 1. Required Properties

The characteristics of the grand piano, whether it is an accompanying or solo instrument, include the corresponding **quality of the tone** (i. e. the spectrum) with **breathing processes in time, a wide dynamic range,** with a wide timbral range corresponding to it it and **smooth transitions** between these all named parameters.

Quality of tone: a quality piano tone is often characterised by adjectives such as sonorous, but also round, full, carrying, etc. In reality, this corresponds to a harmonic spectrum that should be balanced up to the eighth, ideally the sixteenth harmonic component. This means without significant spectral kurtosis (prominent individual components) or "significant inequality in the harmonic spectrum" [5]. It is not decisive whether the moduli of the higher harmonic components in the spectrum decrease linearly or exponentially. If harmonic bands above the 16th component are added, tingling and even buzzing noises will be added to the timbre (undesirable for treble region, but also quieter basses). A homogeneous (round or solid) timbre can also be disturbed by a greater number of phantom partials. The principle of breathing of the tone was described in the section on piano voicing.

Basses with better string elasticity should perform better with a wider dynamic range on a piano, the higher three and four row octaves already have stiff strings and therefore the dynamic performance and dynamic range should be narrowed in these positions. However, the dynamics of the piano are completed by the weight of the hammer and the mechanics/converter from the keys to the hammer. From the measured values, we therefore see that in the middle range the Ant. Petrof can have a wider dynamic range (23-24 dB) than in the bass (around 21-22 dB) and in the high treble range even wider (somewhere up to 28 dB). By a wide timbral range, we mean that the piano in the quiet dynamic position generates a narrow spectrum, i.e. a soft one, and as we move into stronger dynamics, the spectrum will expand and become fuller, more powerful and sharper. Even though the individual parametres are changing for each note, they should keep a smooth overall curve without any significant shifts when assembled into a matrix.

8. 2. Differences between the two product lines

After comparing the parameters, we can say that both instruments show a slight disparity when looking at the decay times envelopes lined up in the horizontal direction (from the four-line octave to the sub-bass). However, it still remains within the given dynamic level (tolerance of 10 dB). It does not exceed it. When it comes to decay time, the Mistral stands out with a smoother curve. The Ant. Petrof brand achieves greater performance and dynamic range compared to the dynamically flatter Mistral. However, the Mistral keeps a consistent pattern of decreasing dynamics in the *ff, f, mf* and *p* levels (see figure 14, yellow marked curves). The Ant. Petrof is much more broken up in terms of the dynamic band levels across the 88 keys (see figure 13, red marked curves). As for the consistency of timbres in the horizontal direction (from low to high notes), both grand pianos show more fluctuations being present in the curves of spectral centroids (within a fifth to an octave, sometimes even more). The curves would become more uniform if we would lower the piano lid in a more closed position or place the measuring microphone further away.

Note: On the other hand, the open piano lid belongs to common practice today at concerts and in studios.

The Ant. Petrof brand has a much wider timbral range (vertical depth) than the Mistral, but it is more "timbre-broken" in the horizontal direction (from low to high notes).

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