Measurement of Acoustic Violin Spectra and Interpretation using a 3D Representation

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Abstract:

The purpose of this work was to find a correlation between a violin's acoustic spectrum and its tonal qualities. Since the measurement of the acoustic spectrum of a violin is quite critical a sophisticated measurement setup consisting of a dedicated exciter [first used by Dünnwald] and an array of eight microfones in a semianechoic chamber was developped.

A great problem is still the recognition of the tonal qualities from the acoustic spectrum: To ease the interpretation of acoustic violin spectra a new representation of the spectrum is presented using a 3D picture. Every fundamental tone of the playing range of the instrument is grouped together with its harmonics and thus enables a much more direct comparison with the acoustic impression when playing the instrument. This 3D representation gives a more global picture of the acoustic qualities of an instrument and many discussions with musicians and violinmakers proved that clear indications of the acoustical qualities of an instrument can be deduced.

The above described set-up is installed pemanently at the Cremona Violin Making School .

Zusammenfassung:

Ziel dieser Arbeit war es einen Zusammenhang zwischen den tonlichen Qualitäten einer Geige und ihrem akustischen Spektrum zu finden.

Um eine präzise Messung des akustischen Spektrums zu gewährleisten wurde die Geige mit einem elektromagnetischen Exciter [nach Dünnwald] angeregt und der Schalldruck im schalltoten Raum an acht verschiedenen Punkten gemessen.

Ein großes Problem ist nach wie vor das Ableiten der tonlichen Eigenschaften eines Instrumentes anhand des akustischen Spektrums: Um die Interpretation des akustischen Spektrums zu erleichetern wurde eine neuartige Darstellungsform gewählt in Form eines dreidimensionalen Spektrums gewählt. Jeder Grundton wird zusammen mit seinen Harmonischen dargestellt und ermöglicht so einen viel klareren Vergleich mit dem Höreindruck beim Spiel des Instruments. Das

3D Spektrum gibt einen viel globaleren Eindruck der akustischen Eigenschaften eines Instrumentes wieder und viele Diskussionen mit Musikern und Geigenbauern zeigen, daß man klangliche Eigenschaften einer Geige aus dem 3D Spektrum ableiten kann.

Der Meßaufbau ist fest an der Geigenbauschule Cremona installiert.

1. Introduction:

From the physicists point of view the violin's sound spectrum -e.g. sound pressure or sound intensity normalised by the exciting force or acceleration -characterises entirely the acoustical behaviour of the violin body.

It should therefore be possible to deduce a violins tone quality from its sound spectrum. Two major problems arise however when one tries to find such a correlation between the violins sound spectrum and its tonal character;

First: The sound spectrum is difficult to measure. Usually one needs an anechoic chamber and an array of several microphones arranged on a sphere surrounding the instrument. Unfortunately the tonal character lies hidden in the fine structure of the sound spectrum, so a precision of about +-1db is needed for not loosing these necessary details. Meinel [1] confirms that a high precision is needed. The excitation is not less critical: To have an excitation situation similar to the normal playing conditions one should excite the instrument at the supporting point of the string at the bridge. The excitation direction is also very important. Weinreich[2] has shown that the violin monopol radiativity is less sensitive of about 20db when excited perpendicular to the string motion in respect to the parallel excitation direction. Weinreich had the transducer positioned on top of the bridge.

Currently the best excitation system seems to be the "Dünnwald wire"[3,4,5]. His transducer adds only a negligible mass of about 20mg to the moving mass of the bridge. His measurements show also visible changes in the sound spectrum when masses of more than 0.1g are added to the bridge.

Unfortunately due to the many different measurement set-ups used in earlier publications it is very difficult if not impossible to compare those measurements. One can only hope that in the future a valid standard for measuring sound spectra will evolve.

The second great problem is the definition of tonal quality: When someone is talking about the tonal qualities of an instrument and everybody is using a different personal vocabulary to describe one's impressions. How can one therefore scientifically characterise a tonal character? It is also important to separate different sensations: Old violins are often preferred because they tell just by their appearance the history of several hundred years. This definitely pleasant feeling must never influence you in a sound judgement [it is evidently this feeling that the international art market is living form] . My opinion is that among those highly quoted instruments there are many normal sounding ones. I have heard Guarneri, Montagnana and other classic Italian, French or German instruments that were not convincing at all. Without doubt there is a difference between a new and a century long played instrument and I will discuss my impressions in the last part of this paper.

As a consequence it is not sufficient to categorise a violin's tone just by its age or by its origin. To get a more detailed picture of a violins tone quality I usually have the violin played by a skilled player and in the following discussion we try to find a correct description that is then written down in a questionnaire.

Of course I do present the musician the registered sound spectrum. I had many discussions with musicians, and most of them revealed the main problem of the sound spectrum: The usual representation [a 2D plot with the log amplitude versus frequency] is too abstract to be compared to a musicians impression. The sound spectrum failed to give answers to such simple questions as: "How can I see from the spectrum that my violin sounds harsh on the g string?"

Therefore a more adapted representation of the sound spectrum was introduced using a 3D picture. As has shown practice it is now much easier to read the resulting spectrum and to compare auditive impressions with this spectrum.

2. Previous work:

The interpretation of frequency response functions (FRF) of violins has always been a great problem. Meinel[6] has done extensive research already in the 1930's and noted in particular the dependence of the plate resonance frequencies on the plate thicknesses Lottermoser and Fr.J.Meyer[7] investigated the formant distribution of old and new violins. Both Meinel and Lottermoser/Meyer used a simplified representation of the FRF of a violin. The FRF divided into 6 to 9 areas and the amplitude of one area was calculated as the average value of the FRF in that area. These simplified FRF's served then as a basis for the interpretation of the spectra.

The most recent work was done by Dünnwald[3,4] He developed a special excitation system for violins that ensures a minimum influence by the excitation system and used then a data base of more than 100 FRF's to find an objective description of the "Italian timbre".

Another interesting method for visualising a violin spectrum using also a 3D representation was cited by C.M.Hutchins[8], the author got to know this method however only recently.

Beside all technical problems of the correct registration of a FRF a fundamental problem is that sound perception is very subjective. A "nasal" timbre for one person might be "beautiful" for another. Therefore the first task (this point alone might already be unresolvable) is to define a common vocabulary to describe timbre.

3. A remark on sound tests:

It is well known that sound perception is very subjective. The violin seems to be an instrument especially difficult to judge and judgements by different people can be quite contradictory. A general and very "human" problem is that the musician and the listener can be influenced by the instruments value and appearance.

On the other hand for the construction of (or the modification into) a good sounding violin a complete awareness of an instruments tonal qualities is required. After having listened to many instruments for the last three years on occasion of the registration of violin FRFs I have found some criteria that make it easier to find a sound description that is accepted by everyone:

-Skilled player:

Instead of playing the instrument myself I prefer to have the instrument played by a skilled violinist . Despite the fact that I often have different violinists at disposition for a violin sound test, it is usually possible to get a valid valuation. Precise questions are however necessary to have the musician try out the appropriate properties of the instrument.

-Clear questions and ask for Power, Playability and Timbre:

It is easily possible to loose oneself in foggy descriptions of a certain auditive impression. To avoid this I typically ask for only three characteristics. These are **Power**, **Playability** and **Timbre**. Each of the four strings is however judged separately .

The Power of an instrument is usually better rated by the listener, the musicians impression at the ear is sometimes quite different (instruments that are penetrant or seem very powerful at the ear often do not radiate well while sometimes instruments that seem less powerful at the ear are projecting well) .

Under playability I understand properties like an easy response, a precise attack, great sensibility or the ability to form many different colours on an instrument.

Usually the timbre is the point that is most difficult to judge. If the player has difficulties in finding a suitable adjective, I present him a list of possible adjectives. This procedure -using a limited number of adjectives for the description of the timbre- also helps cataloguing and recalling judgements later in a database.

In order to obtain clear results it is also important to write down only the characteristic attributes of a violin's playing qualities. For example if an instrument is very normal in its playability I don't write down anything concerning the violins playability.

-Damped rooms:

Playing an instrument in a reverberant room makes it almost impossible to judge it. I prefer rooms that are as damped as possible since a violin's characteristics are exposed more openly. My experience is that an instrument that sounds well in an heavily damped room will also sound well in any other location.

-Instrument in good playing conditions:

Adjust an instrument before testing it: Although bridge and soundpost cannot alter an instrument's character , they do have great influence on the playability and easy response of an instrument. and they can balance a previously unbalanced instrument. The strings should not be too old, especially the G and D strings on violins sound much more covered when played out!

-Correlation directivity-projection:

My impression is that there exists a correlation between the directivity of an instrument and its projection in a concert hall. Listening to certain instruments one has the impression that the sound comes from everywhere. Other instruments can be located much more easily; the sound seems to arrive only from the instrument itself and from no other direction. Those instruments that are much less locatable seem to have a better projection.

-Play scales:

Initially I ask the violinist to play scales on the instrument. The differences in the timbre can be perceived much easier than when playing a Bach Partita. Of course it is indispensable to play music in a second step when judging an instrument.

-*Have a known instrument as a reference at hand:*

When conducting sound adjustments on an instrument it is wise to have a known instrument as a reference. Confront the sound changes always to the reference instrument, otherways you might get confused.

4. The measurement of the sound spectrum:

4.1 Radiativity

The physicists fingerprint of the acoustical qualities of a violin is its sound spectrum. The term sound spectrum is however not a well defined quantity in physics. Meinel[6] has measured the FRF of a violin and the Magnitude of that function represents the Sound Pressure (SPL) relative to the input force. Also Lottermoser/Meier and Dünnwald used the FRF to represent the violin's sound spectrum[7].

Since all the above measurements were done with just one microphone a complex representation of the sound spectrum using the FRF with Magnitude and Phase is meaningful.

Unfortunately the sound radiation of the violin is distributed quite irregularly in space. It is therefore necessary to average the sound pressure over several microphone positions around the violin. One possibility is to average the magnitudes of each FRF , another method is to measure only the power spectra of the input force and the microphone signal and to calculate the magnitude of the FRF by dividing the microphone signal power spectrum by the input force power spectrum and then taking the square root.

The FRF measured like this is a quantity very similar to the monopol radiativity defined by Weinreich[2]. I will therefore call the FRF measured in the above defined way the radiativity. The monopol radiativity as defined by Weinreich would be that part of the radiativity caused by the violin acting as a monopol radiator. Modal Analysis show that the first second order plate resonances of the violin appear at about 700Hz. An exception is the torsion of the centre part [C -bouts] of the violin body, this resonance is usually found in the range 330 to 400Hz, this resonance - representing an acoustical short-circuit- is however a very inefficient radiator. Therefore up to about 700Hz the violin monopol radiativity and the radiativity should be identical.

All measurements in this paper are scaled in Sound Pressure (SPL) relative to the input force at the bridge. The Radiativity varies astonishingly little for different violins, values range typically from 0.5 to 3 Pa /N.

To generate a SPL of 94db [~1Pa] with a violin therefore a force of about 0.3 to 2 Newton is required.

At the Cremona Violin Making School the following set-up was used (all measurements were conducted in the schools laboratory):

Environment: All registrations were made in an semianechoic chamber with dimensions $2 \cdot 2 \cdot 3$ m.

Excitation: The violin was excited by an electromagnetic transducer first used by Dünnwald[3] . It consists of a small wire that is situated in a magnetic field. Therefore any current passing through the wire will exert a force to the wire that is proportional to the current. The wire was calibrated and gives a sensitivity of about 0.002 Newton per Ampere. The system is linear within +-1.5db between 100Hz and 6400Hz. A calibration of the wire is conducted every 6 months. The moving mass of this Dünnwald wire added to the violin bridge was measured by Hacklinger[9] and turned out to be about 30mg. The wire then touches the violin bridge near the e string as if it were a fifth string. Its excitation direction is parallel to the violin's top plate surface and therefore nearly parallel to the d and a string vibration direction.

Microphones: For the measurement a 1'' Bruel&Kjaer Microphone #4136 is used. The sound pressure at eight different microphone positions around the instrument is measured and the squares of the sound pressure are averaged. Five microphone positions are above the violins top plate, one centrally above, one about 45 degrees inclined towards the button of the violin, one 45 degree inclined towards the neck, one 45 degree inclined to the right and one 45 degree inclined to the left.

Below 3 microphone positions were used ,one centrally below the back plate ,one shifted about 50cm to the button and the last position was situated 50cm shifted to the neck .All microphone positions are distant about 75cm (+-20%) from the violins centre. The measurement set-up is also described in [10]. I was curious to know whether the 8 microphones were sufficient to give a good average of the sound pressure of the spatially irregularly radiating violin. I performed a test by rotating the violin relative to the microphones for about 20 degrees. If a significant part of the sound pressure were not be registered by the microphone array then one should expect a change in the averaged sound pressure after the rotation of the violin. Fortunately this was not the case and the second measurement differed form the first by less then +-1db. One can therefore safely assume that an array of 8 microphones is sufficient to measure the violin radiativity.

The data is acquired by a Bruel&Kjaer BK2034 FFT analyser and the violin is excited with pseudo random noise. Other measurements exciting the violin with a swept sine imposed to the BK2034 via software showed almost identical results so that the faster data acquisition via pseudo random noise excitation was preferred. The result was then stored in B&K Total Documentation Format on a PC. The Total Documentation Format contains the Auto Power of channel A [GAA] (square of the force of the Dünnwald wire, the Auto Power of channel B [GBB] (averaged squares of the Sound Pressure of the eight micro positions) and the Cross Correlation [GAB]. The Auto Power of channel A is then compensated by the calibration of the Dünnwald wire. To get the radiativity one has to calculate

$$Radiativty = \sqrt{\frac{GBB}{GAA}} \qquad (1)$$

4.2 Noise Reduction:

The way to calculate the radiativity simply from the power spectra of channel A and channel B of the FFT analyser is not the optimal method. It is however the most convenient method since GAA and GBB are readily available from the FFT analyser.

Problems arise when the signal is contaminated by noise. In our case noise might add to the microfone signal and GBB will show greater values.

A solution is to calculate the radiativity from the cross correlation GAB[11] ; in the presence of noise in the output signal the radiativity is best approximated by :

$$H1 = \frac{GAB}{GAA},$$ H1 is the transfer function.

To get the radiativity on has to measure the transfer functions H1 for all 8 microfone positions. The radiativity will then result as the average of the magnitudes of the transfer functions.

$$Radiativity = \frac{1}{n} \cdot \sum_{\substack{micro \\ positions}}^{n} Magnitude(H1) \quad . \qquad (2)$$

This calculation must however be acomplished on a computer since the FFT analyser is averaging the real and imaginary part of H1 seperately.

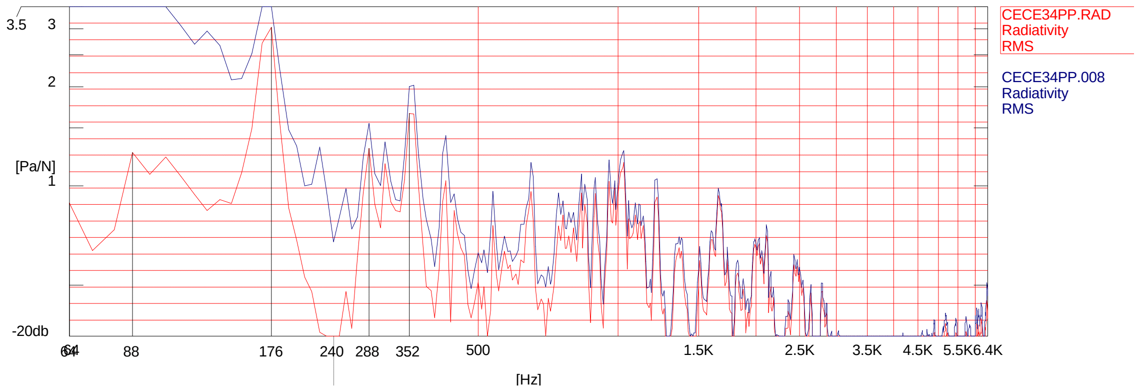


Fig. 1 shows the radiativity of a violoncello to demonstate the difference in the practice between the radiativity calculated according to (1) and (2). cece34pp.rad is calculated according to method (2) and cece34pp.008 is calculated after (1). Clearly visible is the high noise at low frequencies [below ca 250 Hz] when method (1) is used. I purposely use a violoncello spectrum here as example because the measurement set-up limits show up much more clearly.

Serial Recording:

To further improve the signal to noise ratio the violin was no longer excited with pseudo random noise, but a variable sine wave was used [imposed via software to the BK2034 FFT analyser] .The microfone signal was then filtered from all signals with frequencies different than the excitation frequency. The input and output signal were in this way raised a net 40 db relative to the parrallel excitation.

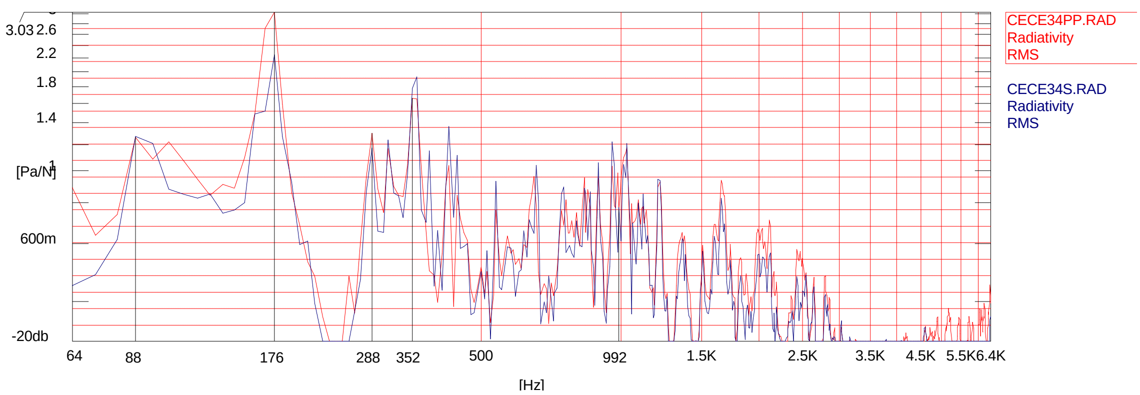


Fig. 2 shows again the radiativity of a violoncello. Cece34s.rad is the radiativity resulting from a serial recording. Cece34pp.rad is the radiativity resulting from a parrallel recording. Both times calculation method (2) was used. The difference between the two measurements is surprisingly small and is therefore a proof that parrallel excitation can be used for the measurements.

Currently I use a combination of both methods: The frequencies below 320Hz are measured using a variable sine wave excitation. The higher frequencies are measured using the pseudo random noise excitation. This compromise saves a lot of time with respect to a pure serial recording but does not sacrifice any precision of the measurement. A complete measurement can thus be conducted in about 20 minutes.

5. The vibrating string:

As I already stated above it is quite difficult to deduce a violins tone qualities from the sound spectrum. This is in part due to the fact that the natural playing situation is little comparable to the sound spectrum. Since the violin is excited by a vibrating string, the input spectrum at the bridge is in a first approximation equivalent to the spectrum of a vibrating string (in a better approximation the spectrum of the vibrating string is modified for the case of a string supported at one end on a point with a certain admittance, the admittance of the violin body). The spectrum of a vibrating string is however quite well known; it consists of a fundamental frequency defined by the length of the string and its harmonics. Fig.3 shows a typical velocity spectrum of a vibrating d string. The harmonic structure of the spectrum is well visible, interesting is the fact that many harmonics [up to about the 20.th] are present in the spectrum. For completeness the time signal is also presented to show the deviation from the theoretical triangular shape. The reader is referred to Cremer[12] for more information on theoretical studies of the string motion

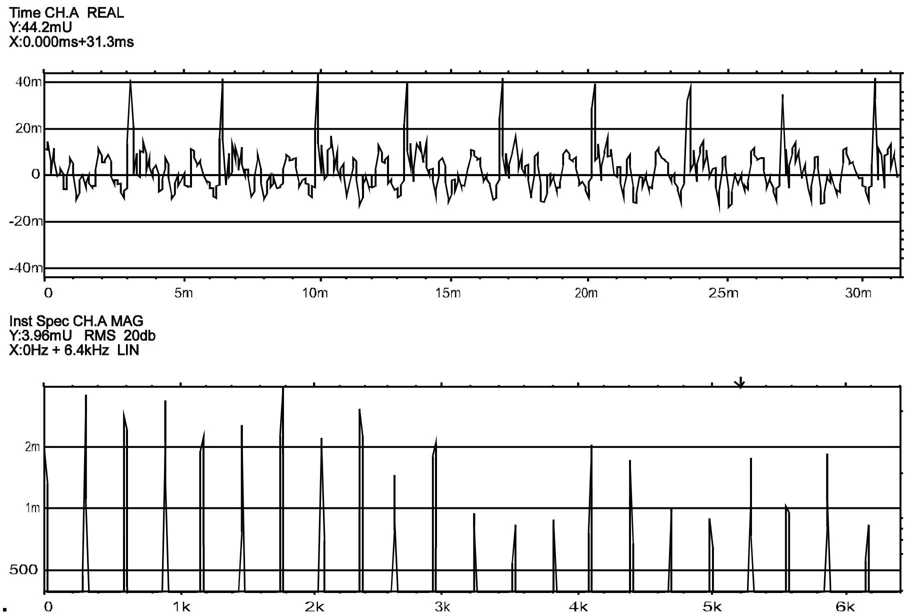


Fig.3, Time and spectrum of the velocity of the d string at the supporting point at the bridge. The measurement was done with a phonograph needle [calibrated] put on the bridge while playing the instrument with the bow on the d-string. The distance bow-bridge was about 2cm. The velocity spectrum and the force spectrum of a vibrating string differ only by a constant factor from each other, the wave impedance of the string.

To get the Sound Pressure spectrum of the violin when played on the note d 292Hz on the d string one simply has to multiply the force spectrum of the bowed string [Fig.4a] with the sound pressure spectrum [Fig.4b] of the violin. The resulting sound pressure spectrum [Fig.4c] represents the acoustic output of the instrument when that note is played and is now easily comparable with the auditive impression of the musician.

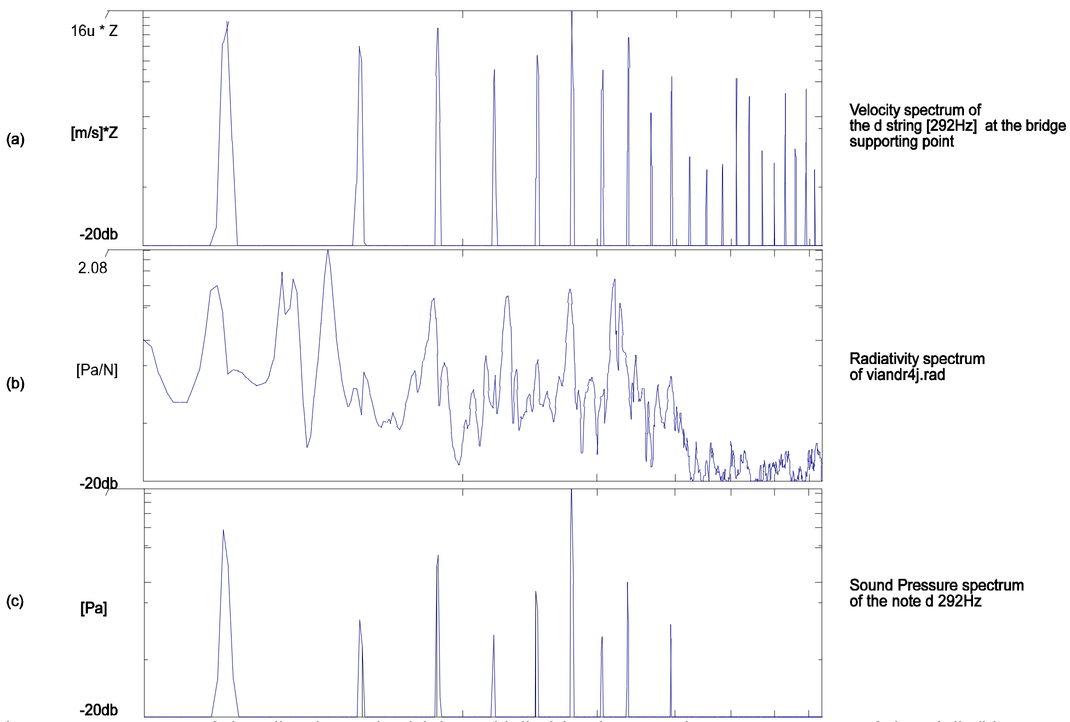


Fig.4 . The Force spectrum of the vibrating string(a) is multiplied by the sound power spectrum of the violin(b) to result in the sound power output due to the string force(c).

6. A 3D representation of the sound spectrum:

As is seen from the above bowed string spectrum all stringed instruments are always excited by a number of frequencies simultaneously. These frequencies are simply the harmonics of the string vibration. The relative amplitudes and phases of the single frequencies depend on the bowing speed, the contact point and the bowing pressure. A slight inharmonicy of the frequencies can be caused by the stiffness of the string and other second order effects.

Fig.5 shows a typical sound spectrum. For easier reading of the sound spectrum it was tried to group together one fundamental frequency and all its harmonics.

Fig.5a shows this for the case of the fundamental frequency of 293Hz.

The y-axis is scaled in frequency and only the multiples of the fundamental frequency are drawn with their relative amplitudes. The amplitudes of the harmonic frequencies are the absolute amplitudes taken from the conventional sound spectrum. This means that all amplitudes are relative to the same excitation force. One can think of this spectrum in Fig.5a as being the sound pressure of the note d when played on a fictive string with all harmonics in the string spectrum having the same amplitude.

To obtain a picture of the whole instrument the procedure of Fig.5b is repeated for every note within the playing range of the instrument, but the graph is now drawn with the origin shifted versus the x-direction.

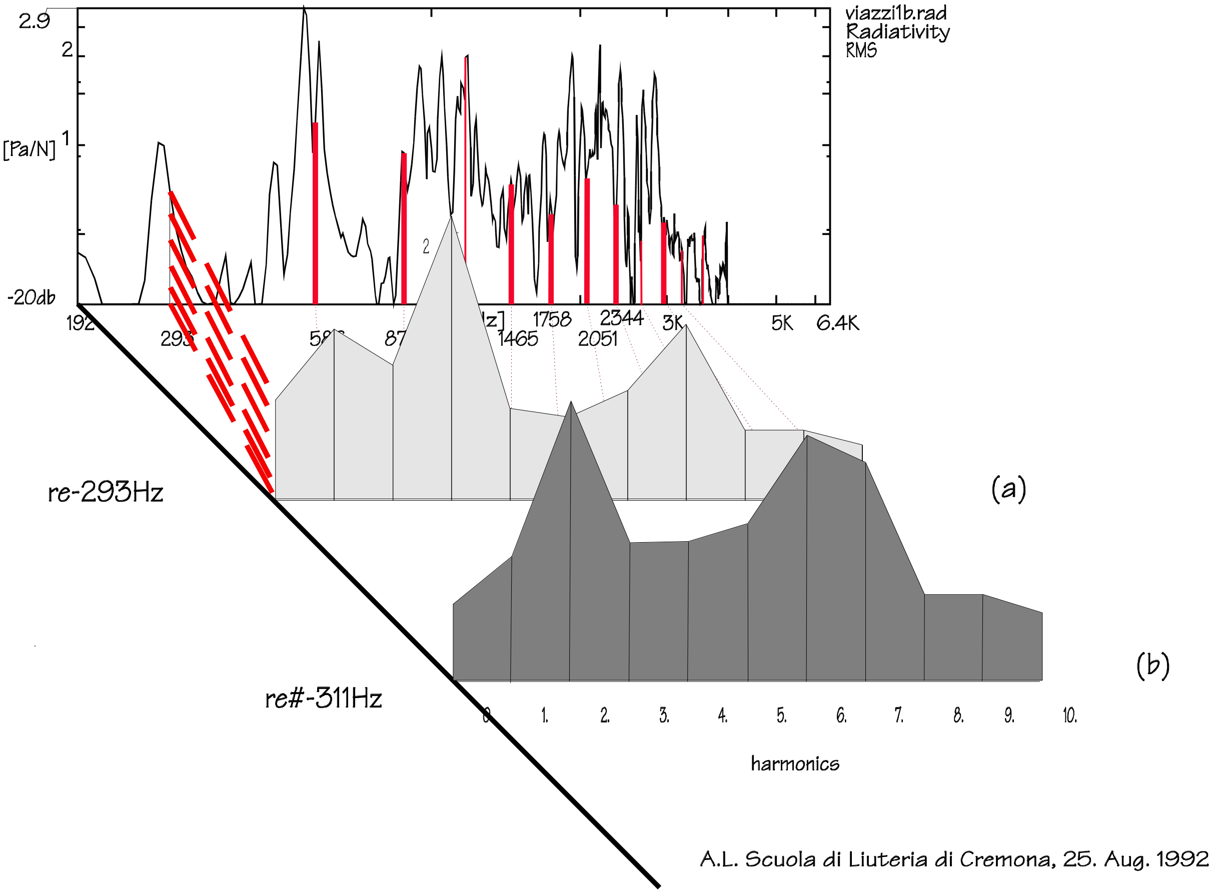


Fig.5 grouping together the harmonics of every fundamental frequency results in a easier reading of the acoustic spectrum of the violin.

The final result is a 3D landscape that represents the tonal qualities of the instrument.

Fig. 6 shows the 3D plot corresponding to the sound pressure spectrum of Fig.5a.

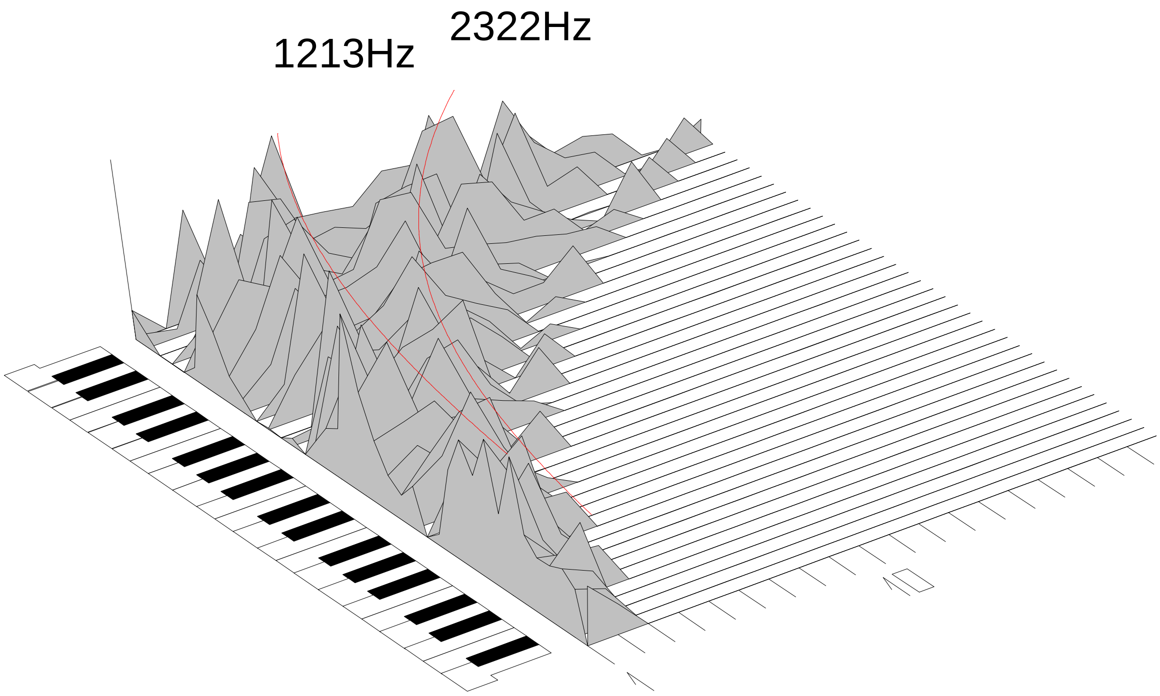


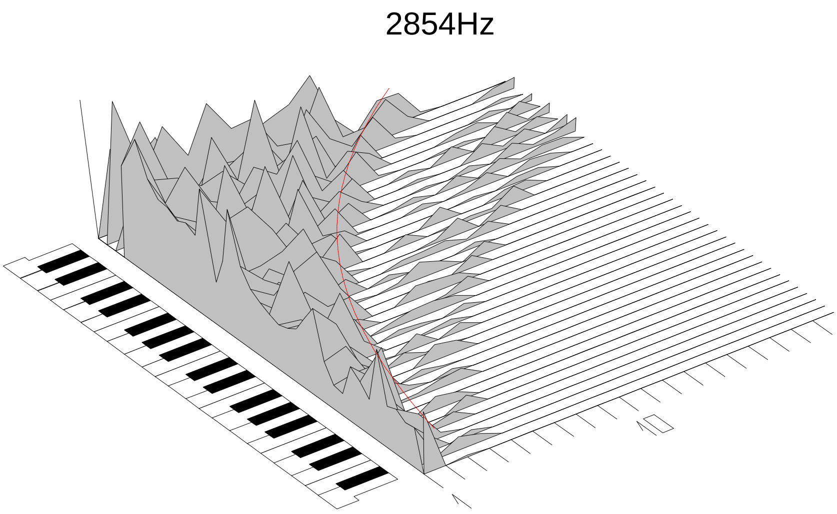
Fig.6. The 3D plot of the radiativity spectrum of Fig.5.
The x-axis represents the frequencies of the playable notes of the instrument. A piano keyboard is drawn to symbolise the playable notes on the violin. The y-axis represents the number of the harmonics relative to the note on the x-axis. The z-axis represents the amplitude. The same scale is is used as in Fig.5.

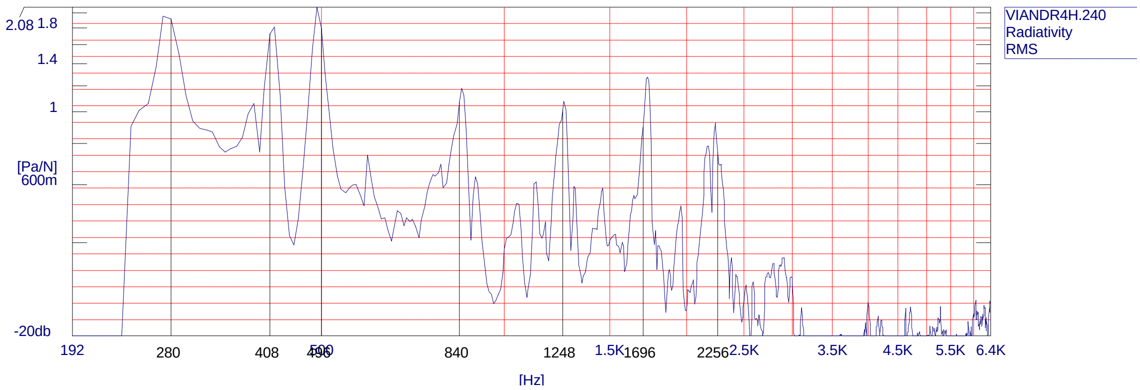
The 3D plot must be read differently than a usual sound spectrum: One single resonance shows up in the 3D presentation as a curved mountain chain. See the resonance in Fig.6 at 2322Hz. This representation demonstrates also that the resonances at higher frequencies are more important for the violin's acoustical behaviour than the resonances at lower frequencies. Since all notes that lie below a certain resonance are influenced higher resonances influence more notes than lower ones. For notes that lie close below the resonance, the resonance will raise the lower harmonics of that note. For notes played on the violin that have their fundamental frequency much below the resonance in question, that resonance will still raise the higher partials. Resonances at lower frequencies are therefore less important because they do influence a smaller number of notes.

In comparison to the 2D Sound Power spectrum it is much easier to see what notes are influenced by a certain resonance. For example here in this 3D spectrum there is a strong resonance at about 1200Hz, clearly visible as a mountain chain. This resonance helps to raise the lower harmonics of the notes from about g 392Hz up to d- 1200Hz. It is also clearly visible that this resonance is responsible for the high amplitudes of the higher harmonics of the lower notes on the g string, namely g-196Hz up to about c-272Hz. One expects a harsh timbre on these low notes due to the over represented high harmonics and this interpretation was in fact confirmed by the sound test.

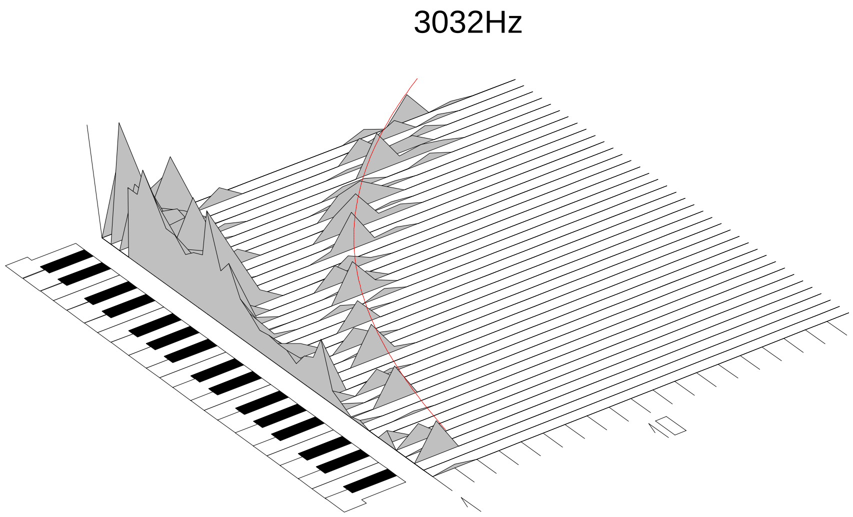
7. Example spectra:

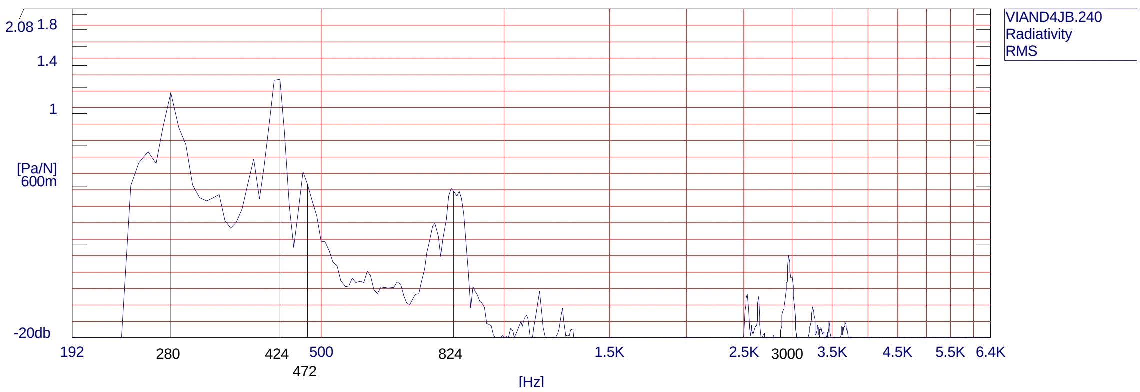
Example 1. a good modern violin, 4 months old, very well balanced, with a full, rich and dark timbre, very powerful basses, but slightly muted at high frequencies on the e string.



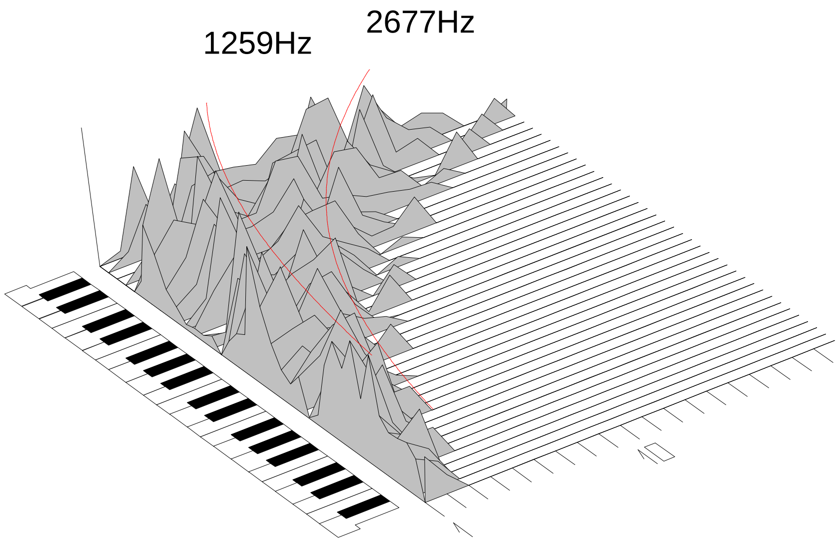


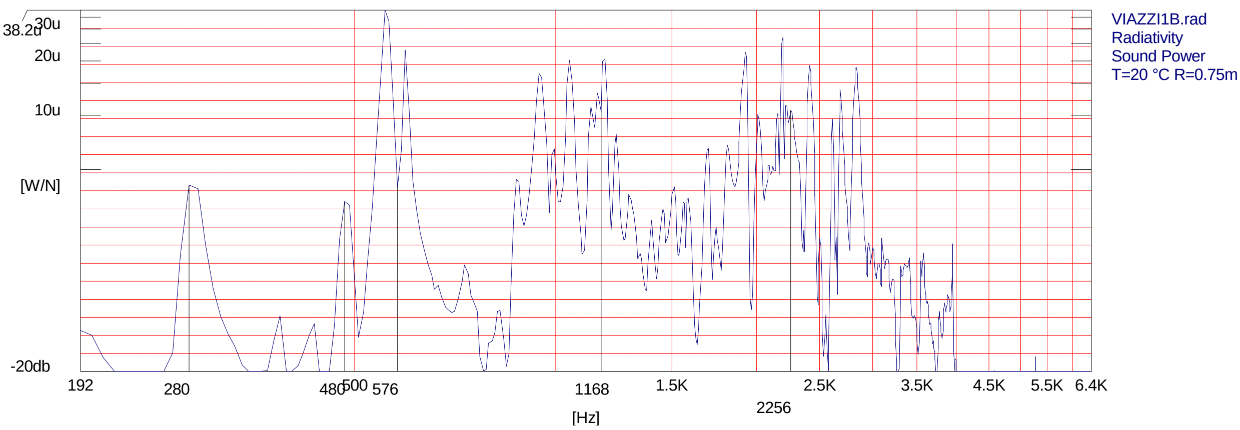
Example 1a. The same instrument as 1., but with a 5g mute attached to the bridge.



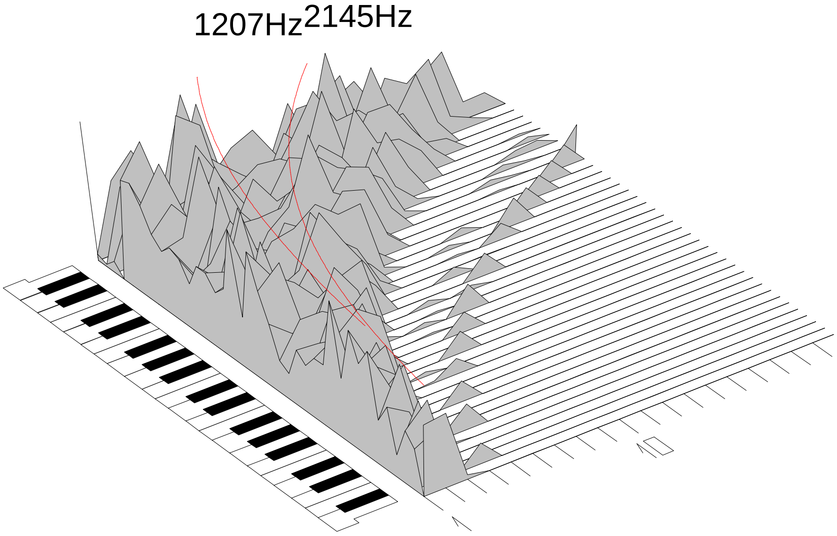


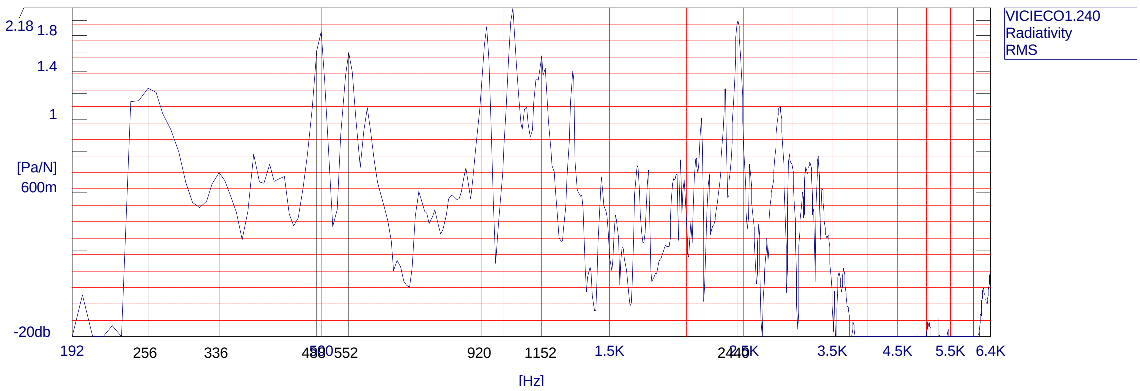
Example 2. an Italian instrument made at the end of the 19. century, probably by Antoniazzi, but labelled E.Ceruti 1867. This instrument is very present at the ear, but the timbre is harsh all over, if not even metallic on the e string. The g string is harsh and has little power because it squeaks already at mezzo forte.



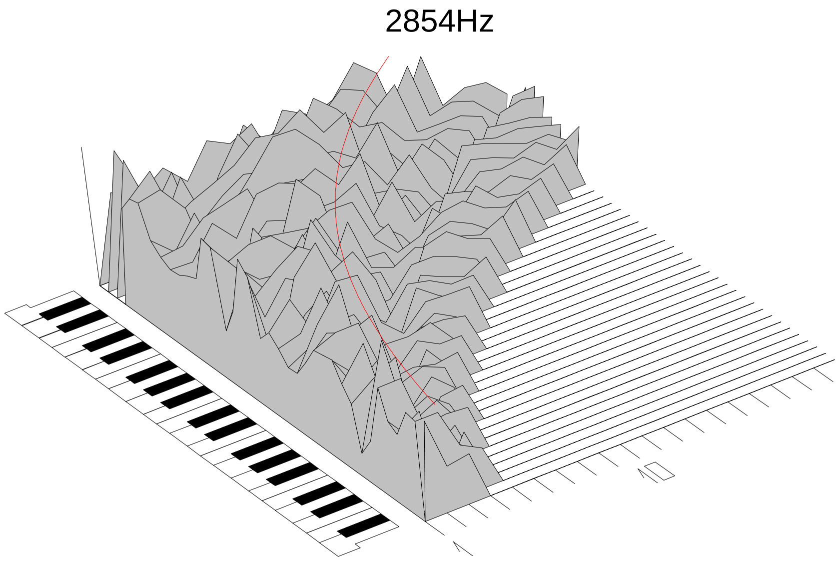


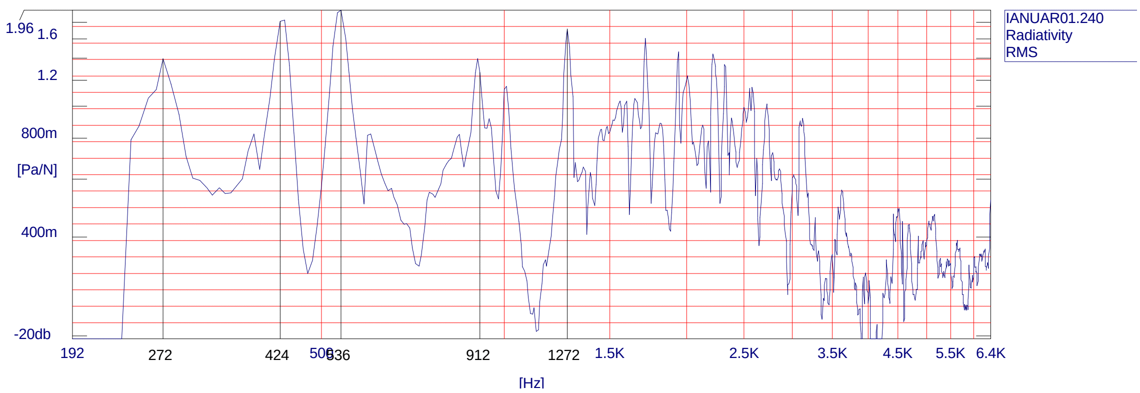
Example 3. a student instrument , generally a very metallic timbre,





Example 4. a very sweet sounding Italian instrument, made about 1650 by Iacobus Ianuarius in the work shop of Nicolo Amati. This instrument has a "soprano" like voice, a very brilliant and rich timbre at higher frequencies. A very sensible instrument ,but not too sweet. The lower strings lack power however so that this instrument is only suited for chamber music.





Quality criteria:

A correlation has been found between an instrument's sound quality and the following criteria of its 3D spectrum, the **evenness** of the 3D spectrum, the **slope** and the **individual ridges** in the 3D formation. Please keep in mind that the following results are based on the analysis of only about 60 violins. A more scientifically correct interpretation must involve a much higher number of instruments and maybe a more rigorous procedure when playing the instruments. I hope to collect more spectra in the future for a further validation and refinement of the results.

Evenness:

Confronting many 3d spectra it turned out that all instruments judged to be good instruments by the musician had this quality in common: The 3D formation of the sound spectrum was always very dense and even and without significant drops. The spectra of the Ianuarius [example 4] and the modern instrument viandr4j.240 [example 1] fulfil this requirement. No trenches are visible and the formation is spread rather uniformly in the whole frequency range. The other 2 example spectra presented above show evident drops in their 3D spectrum:. The Antoniazzi spectrum consists mainly of two single ridges, at about 1200Hz and a broader one at about 2300Hz (see the cursors). All the other areas of the spectrum are sparsely filled. Also the spectrum vicieco1.240 [example 3] shows significant drops, here one large trench is visible, between 1400Hz and 2200Hz. In my view it is a necessary condition to have a smooth course of the 3D formation without any trenches for having a good sounding violin.

The slope of the 3D formation:

The general run of the 3D formation determines the timbre of the instrument. Although the problem of defining timbre is very difficult to resolve, some intelligible rules seem to exist: A relatively high area at low frequencies yields an instrument with powerful basses and often a darker timbre.

A general tendency to decline smoothly versus the higher frequencies will generally correlate with a pleasant timbre. If the slope declines too fast then the instrument will sound covered. The instrument viandrj4.240 [example 1] gives an example of such a behaviour. This instrument has a pleasant timbre, but the more pronounced decline above 3000Hz gives the impression of a slightly covered tone. An ascending slope versus higher frequencies will yield an annoying timbre. Some student instruments measured show this tendency. The spectrum of a violin with a mute on the bridge is presented as example 1a. The attenuation of the higher frequencies above about 1kHz is clearly visible.

The difference between antique and modern instruments:

Any musician will tell you immediately whether the instrument he is playing on is an antique instrument or a modern one. This difference is however only evident to the player, a listener will not necessarily be able to decide whether the instrument he is listening to is an antique or a modern one. How does the violinist describe this difference? The most often heard answer is that old violins have a clearer, dryer tone emission than modern ones. Extraneous noises to the tone emission are also lower on older instruments. Sometimes the antique violin's timbre is described as richer, fuller and more lively. Another easy to note difference is the decay time of the plucked string. Good old instruments have often a much longer decay time.

Examining the 3D and conventional sound spectra I have yet failed to find a general difference between antique and modern instruments. At least the longer decay time of antique instruments should manifest itself in a higher Q-Factor of the resonances, but neither a first visual inspection of the spectra nor the yet unpublished results of Modal Analysis[13] [the damping factors are always between 0.5 and 3% apart from the lowest resonances which have a higher damping] give evidence of this. It could be that this difference lies hidden in the fine structure of the spectrum and were thererfore difficult to detect. As I am still collecting spectra I hope to find an answer to this question in the future.

8. Conclusion:

The main effort in developing the above described measurement set-up and interpretation method was to obtain a measurement chart of an instrument that represents the significant acoustic qualities of this instrument. The 3D view of the acoustic spectrum provides a much better global and less confusing description of the acoustical properties. Once a valid physical description of a system is established [as is in this case the 3D view] one can set out on further projects. The quality of the above developed acoustical description of an instrument can thereby be tested and verified. The next project already under way here at Cremona is the acoustic modification of violins. We will concentrate on the trenches in the 3d view of the acoustic spectrum and try to modify an instrument to raise its acoustic output in this particular region. The modifications will be carried out empirically, but additional information obtained by Modal Analysis and Structural Dynamics Modification[13] will be used.

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Fig. 1 shows the radiativity of a violoncello to demonstate the difference in the practice between the radiativity calculated according to (1) and (2). cece34pp.rad is calculated according to method (2) and cece34pp.008 is calculated after (1). Clearly visible is the high noise at low frequencies [below ca 250 Hz] when method (1) is used. I purposely use a violoncello spectrum here as example because the measurement set-up limits show up much more clearly.

Fig. 2 shows again the radiativity of a violoncello. Cece34s.rad is the radiativity resulting from a serial recording. Cece34pp.rad is the radiativity resulting from a parrallel recording. Both times calculation method (2) was used. The difference between the two measurements is surprisingly small and is therefore a proof that parrallel excitation can be used for the measurements.

Fig.3, time and spectrum of the velocity of the d string at the supporting point at the bridge. The measurement was done with a phonograph needle [calibrated] put on the bridge while playing the instrument with the bow on the d-string. The distance bow-bridge was about 2cm. The velocity spectrum and the force spectrum of a vibrating string differ only by a constant factor from each other, the wave impedance of the string.

Fig.4, the Force spectrum of the vibrating string(a) is multiplied by the sound power spectrum of the violin(b) to result in the sound power output due to the string force(c).

Fig.5 grouping together the harmonics of every fundamental frequency results in a easier reading of the acoustic spectrum of the violin.

Fig.6. the 3D plot of the radiativity spectrum of Fig.5.
The x-axis represents the frequencies of the playable notes of the instrument. A piano keyboard is drawn to symbolise the playable notes on the violin. The y-axis represents the number of the harmonics relative to the note on the x-axis. The z-axis represents the amplitude. The same scale is is used as in Fig.5.

Example 1. a good modern violin, 4 months old, very well balanced, with a full, rich and dark timbre, very powerful basses, but slightly muted at high frequencies on the e string.

Example 1a. The same instrument as 1., but with a 5g mute attached to the bridge.

Example 2. an Italian instrument made at the end of the 19. century, probably by Antoniazzi, but labelled E.Ceruti 1867. This instrument is very present at the ear, but the timbre is harsh all over, if not even metallic on the e string. The g string is harsh and has little power because it squeaks already at mezzo forte.

Example 3. a student instrument , generally a very metallic timbre,

Example 4. a very sweet sounding Italian instrument, made about 1650 by Iacobus Ianuarius in the work shop of Nicolo Amati. This instrument has a "soprano" like voice, a very brilliant and rich timbre at higher frequencies. A very sensible instrument ,but not too sweet. The lower strings lack power however so that this instrument is only suited for chamber music.

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