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

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1. Introduction: Looking at the process of sound generation while playing on a violin it turns out that this process involves quite many parameters: The bow, the bridge, the room, the strings, the violin body, the musician are all contributing to the sound. The most important role is obviously covered by the musician himself, a fact that in all research of musical acoustics must never be overlooked.

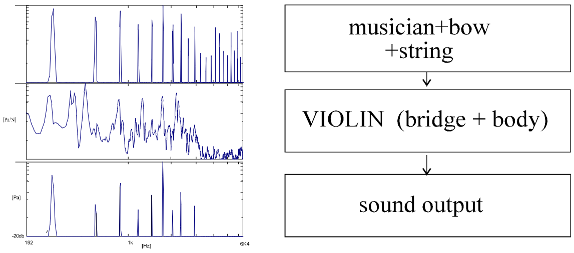

Fig. 1. The note d-293Hz played on a violin.

In a very simplified form the sound generation process can be considered a three stage process (see fig. 1). The first component involves the tone generation process: The musician is driving the strings with a bow, the strings are acting as a frequency generator. The next component is the violin itself, including body and bridge. The violin converts the input force into sound pressure output. Finally, the resulting sound output is represented by the third block of fig. 1. On the left side of fig. 1 an example of the sound generation process is given for the note d - 293Hz played on a violin. The component musician-bow-strings can in physical terms be described by the bowed string spectrum, depicted on the upper left side of fig. 1. The harmonic structure of the spectrum is clearly visible, even the high frequency components are little attenuated (the y-scale covers 20db). This bowed string spectrum was measured with a phonograph needle on top of the violin bridge. The phonograph needle was attached in such a way that even while playing on the violin it would not drop off the bridge. An example of the resulting sound output is given in fig. 1 ,left side, in the lower part. The violin itself can be described by its acoustic spectrum. In fig. 1, left side, middle part, a radiativity spectrum is shown. In this paper the attention will be paid exclusively to the violin acoustic spectrum, on how to measure it, and how to interpret it, a more detailed description of the set-up can be found in (Langhoff 1993).
This division of the sound generation process in the above described three steps has another advantage: Fig. 1 represents a system that can be considered linear. It is true that the interaction bow-string is nonlinear, but this subdivision is not executed and this complex is together with the musician considered as a whole. It is then possible to calculate the impulse response of the violin body from its acoustic spectrum and then to convolute the incoming signal with it to obtain the output signal. Future research will go in this direction as have shown the impulse response sound examples presented (Weinreich, 1993) on this conference. Compulsory for such an approach is however the accurate measurement of the violin's acoustic spectrum.

<u>2. Measurement of the acoustic spectrum, the radiativity:</u> The following set-up is installed permanently at the Cremona Violin Making School, Corso Garibaldi 178, I-26100 Cremona.
The exiter is an electromagnetic transducer based on a design first used by Dünnwald (Dünnwald, 1984). It consists of a small wire that is situated in a magnetic field. Therefore any current passing through the wire will exert a force that is proportional to it. The wire is calibrated and gives a sensibility of 0.002N per Ampere. The system is linear within +-1.5db between 100Hz and 6400Hz. The most important property of it is its low moving mass. Measurements (Hacklinger, 1991) have given a moving mass of only ~30mg. The wire 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. The violin is situated in an anechoic chamber with dimensions 2•2•3m³. The sound pressure is then measured with a microphone at eight positions around the instrument. For each microphone position the frequency response function (frf) is registered with a B&K2034 2 channel FFT analyser.

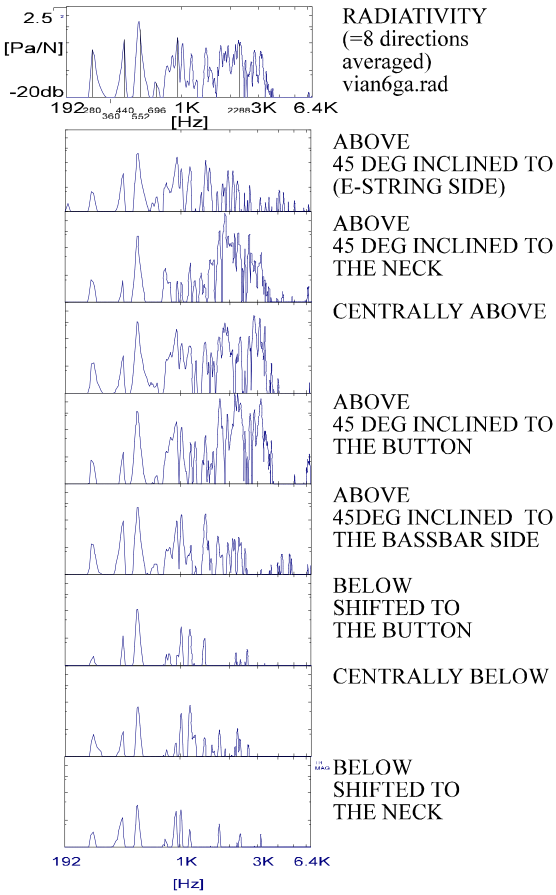

Fig. 2. The radiativity and the frequency response functions (H1,MAG) for different microphone positions.

Fig. 2 shows the frf's of one violin for the different microphone positions. It is surprising that the individual differences are that great, there are differences of 15db for the various directions. Clearly visible is also the fact that the back is radiating less than the top plate, the three frf's taken from the back indicate this by their lower overall amplitude. To obtain a spectrum that most accurately represents the acoustic qualities of a violin it is therefore necessary to consider the sound output in all directions. Averaging the magnitudes of all frf's results in a final spectrum (radiativity) that characterizes much better the violin's tonal qualities. In a real playing situation the listener will also (by reflection) receive sound from many different radiation directions of the violin. This is also confirmed by the below explained 3D interpretation. If only one particular microphone direction was used as a basis for the 3D interpretation, the interpreted sound quality often didn't correspond to the musician's impression. The correlation was much better between the interpreted sound quality and the sound impression by the listener if the averaged spectrum was used as a basis for the interpretation. The averaged spectrum is called radiativity following the notation introduced by (Weinreich, 1983). Also very important for the measurement of the radiativity is the use of a suited exiter. The radiativity is very sensitive to the mass load on the bridge, already 0.2 grams added on top of the bridge change the radiativity significantly at higher frequencies (about -7db above 1KHz has been observed).

3. Interpretation using a 3D representation: From the physicists point of view the radiativity spectrum does contain all the necessary information regarding the tonal properties of an instrument. Examining many radiativity spectra and comparing them to a musician's judgment of the instrument it turned out that a correlation is often difficult to find. One reason is certainly the great number of resonance peaks in the radiativity. Another difficulty in the understanding of radiativity spectra must be contributed to the fact that there is no ideal radiativity spectrum. Different instruments can have completely different tonal characteristics, but nevertheless they all can be good instruments. A valid interpretation of the radiativity must therefore not tell the difference between the measured instrument's radiativity with respect to an ideal instrument. It should however simply try to help recreating the instrument's tonal character while looking at the radiativity spectrum. At this point it is helpful to recall the fact that in a real playing situation (e.g. d - 293Hz) the input signal is composed of a fundamental frequency with many harmonics (see fig. 1). The conventional 2D spectrum does in its representation not take account of the fact that some frequencies are always excited simultaneously. The 2D radiativity spectrum just concatenates the amplitude of the radiativity for consecutive frequencies. In order to correlate better a listener's impression to the violin's radiativity spectrum this spectrum should consist in a graphical picture that represents a violin's tone as played at a time; in fig. 3 such an attempt is undertaken. In the background of fig. 3 you can see a conventional [2D] radiativity spectrum. What happens now, if the violinist plays a d-293Hz? As was previously explained, the violin's sound pressure output now contains the fundamental frequency d-293Hz and a number of harmonics caused by the typical string vibration. The amplitude of these harmonics depends on two factors, the amplitude of the radiativity spectrum at the corresponding frequencies and of the amplitudes of the harmonics of the bowed string spectrum (see fig. 1). In fig. 3a the first eleven harmonics of the note d-293Hz are represented. The amplitude of the single harmonics is just the amplitude of the corresponding frequency in the radiativity spectrum. One can think of this spectrum in fig. 3a 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. The question arises, why in fig. 3a the spectrum of a "fictive" string with all harmonics having the same amplitude was chosen. It is obviously very easy to take account of the bowed string spectrum; a multiplication does the job. But, what bowed string spectrum to use? Every musician will produce a different bowed string spectrum, dependent mostly on the on the bow's contact point, its pressure and its speed. For some contact point certain harmonics of the string will be suppressed, because the contact point coincides with a nodal point of that harmonic. Therefore a

weighting of the radiativity spectrum amplitudes [of the single harmonics] with the bowed string spectrum was not applied. The purpose of the 3D representation is only to "represent" the radiativity. A weighting of the harmonic spectrum in fig. 3a was avoided for this reason too, as a weighting would already be a modification and not only a representation of the radiativity.

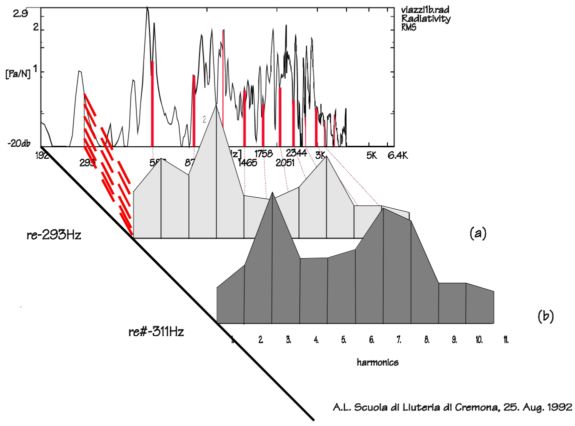

Fig. 3: Grouping together the harmonics of every fundamental frequency results in a easier reading of the acoustic spectrum of the violin.

The procedure to obtain a 3D representation is now straightforward. The harmonic spectrum is repeatedly extracted from the radiativity for all possible notes of the playing range of the violin. Fig. 3b shows the harmonic spectrum for the note d#-311Hz. This graph is shifted with respect to fig. 3a to give a 3D impression . To obtain a picture of the whole instrument the procedure of fig. 3b is repeated for every note within the playing range of the instrument, the final result is a 3D landscape that represents the tonal qualities of the instrument. Fig. 4 shows such a 3D landscape for the same instrument as in fig. 3. The x-axis represents the frequencies of the playable notes of the instrument. A piano keyboard is drawn to symbolize 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 used as in Fig. 3. The spectrum consists of the harmonic "slices" for the fundamental frequencies g-196Hz up to g-1568Hz. By choosing a suitable viewpoint most harmonic slices remain visible and enable a good readability of the 3D spectrum.

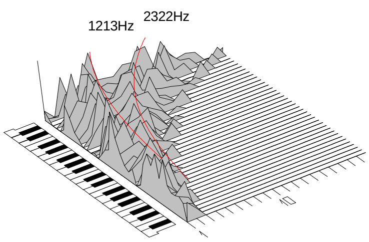

Fig. 4: The 3D plot of the radiativity spectrum of fig. 3. The x-axis represents the frequencies of the playable notes of the instrument. The y-axis represents the number of the harmonics relative to the note on the x-axis. The z-axis represents the amplitude. The same scale is used as in fig. 3.

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. 4 at 2322Hz. This representation demonstrates also that the resonances at higher frequencies are more important for the violin's acoustical behavior than the resonances at lower frequencies. The resonance at 2322Hz influences all notes that lie below that frequency; even much lower notes like the g-196Hz will be influenced: Some higher partials of that g-196Hz will be raised by the resonance 2322Hz. A higher resonance influences -by acting on the corresponding partials- all fundamental notes that lie below it. Resonances at lower frequencies are therefore less important because they do influence a smaller number of notes. In comparison to the 2D radiativity 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. During the last three years the spectra of about 180 instruments were recorded and their 3D spectra were compared to the sound impression. It turned out that instruments with different tonal characters have different 3D shapes.

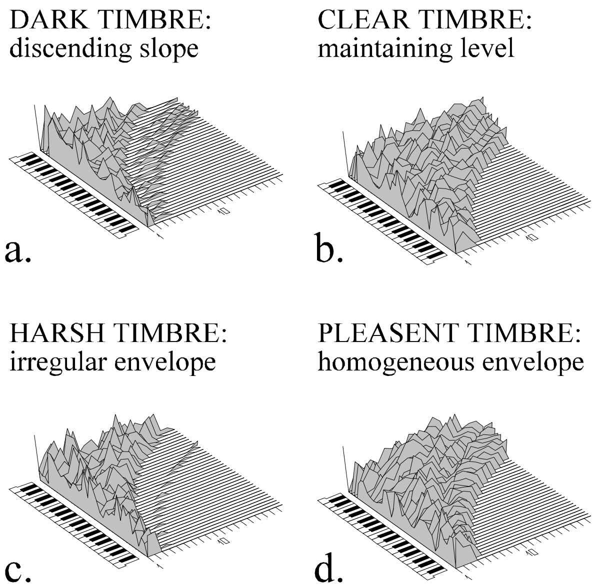

Fig. 5. The 3D spectra of four instruments with different tonal characters.

In fig. 5 four different 3D spectra are shown. The instruments were judged good sounding instruments apart from the instrument with spectrum (c) which belongs has a harsh timbre. Spectrum (c) is also the spectrum that is most difficult to interpret of the four instruments shown in the figure: It has many ripples and is formed quite irregularly. Many mediocre sounding instruments have an irregular spectrum like this. The fact that the musician has often difficulties to give reasons for his negative impression of such an instrument is nicely confirmed by the 3D spectrum: It's envelope is irregular and a tendency is not to observe. Fig. 5a is the 3D spectrum of a dark sounding instrument, slightly covered on the e string, fig. 5b is a very brilliant and clear sounding instrument, and fig. 5d is an instrument with a very pleasant timbre, but lacking power on the lower strings. These three spectra all have different shapes, because each instrument has its own tonal character.

Conclusion & Out view: The 3D representation provides a good global view of an instrument's tonal characteristics. It is also possible to explain why an instrument does not sound well (this is caused by the trenches at certain frequencies in its 3D spectrum). With this knowledge one can then try to modify an instrument, for example with the help of modal analysis. A further test of the above results is underway by recreating the violin sound output from its spectrum, convoluting the impulse response with a measured input signal. One can then modify the spectrum on the PC and then 'relisten' to the instrument. In this way a tonal property is stored as a tonal property and not as a picture, the listeners impression can therefore be recalled immediately. Imagine that you would like to recall your impression of a Rembrandt painting by listening to a musical description of it (in physics this is the normal way to do it!).

Finally, I would like to express my gratitude to the principle of the Cremona Violin Making School Arch. S.Renzi who has placed the Violin Making School's physics laboratory to my disposal.

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