Empirical Tools in Contemporary Violin Making: Part II. Psychoacoustic Analysis and Use of Acoustical Tools

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ABSTRACT

A method for measuring and interpreting the sound radiation of bowed stringed instruments is introduced. The aim is to extract psychoacoustical information from "technical" data in an instrument's resonance profiles. Measured transfer functions ($L_p = p/F$; with p=sound pressure and F=exciting force) provide the input data for calculating specific loudness and overall loudness as a function of playing frequency. Examples are given for violins made by Antonio Stradivari and Joseph Guarneri del Gesu. Although similar in their overall loudness (a quantity relevant to their dynamical potential) and their tone-to-tone fluctuations of loudness (a quantity relevant to their dynamic balance), they clearly differ in their specific loudness patterns, which seem to be useful to describe their tonal color (timbre).

Practical benefits of such acoustical tools in violin making include the following:

a) Understanding correlations (Example: Resonance profile and the effectiveness of the player's vibrato)
b) Parameter studies (Example: Acoustics of the fingerboard)
c) Controlling the process of constructing new instruments (Example: making tonal copies)

PSYCHOACOUSTIC ANALYSIS OF THE RADIATED SOUND

If modal analysis can be thought of as an empirical *diagnosis* tool for the violin maker in order to show the vibrational behavior of an instrument (see Part I), psychoacoustic analysis could be called a *controlling* tool to analyze the resulting sound. Psychoacoustic analysis can shed some light on the question: What are the tonal consequences of the instrument's vibrational behavior?

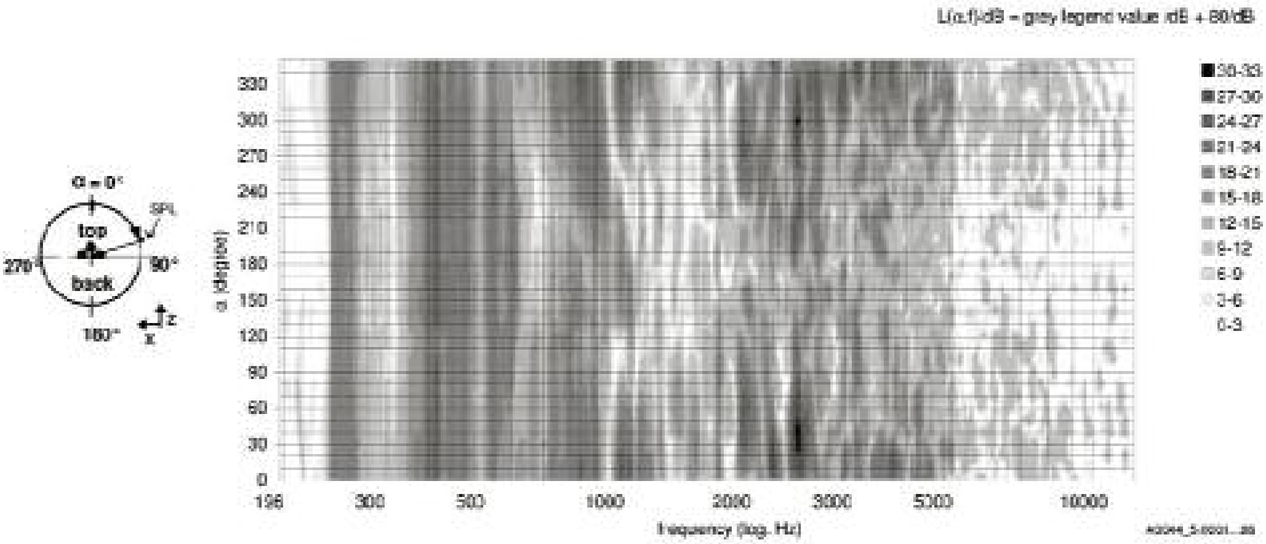
Our method of analyzing and evaluating the sound radiation of a bowed stringed instrument is based on the following six steps:

1. Measurement of the spatial radiation of sound $L_p(f;\alpha) = p(f;\alpha)/F(f)$. The sound pressure level $p(f;\alpha)$ is measured on a circle around the instrument at 36 different angles α_i ($\alpha = 0...360°$; $\Delta\alpha = 10°$; number i of different angles = 36) between microphone and instrument while the instrument is excited by a force F(f) by means of a small impact hammer-pendulum at the bridge. From the excitation F(f) and response $p(f;\alpha)$, the transfer functions $L_p(f;\alpha) = p(f;\alpha)/F(f)$ showing the frequency dependent ratios of sound pressure to exciting force are determined using an FFT-Analyzer (FA-100, difa). The measurements are done under normal workshop conditions, so room acoustics such as reflection, absorption, and room modes have to be taken into account. The effect of room reflections being recorded together with the direct sound offers a certain advantage: some averaging occurs over the various radiation directions, even for a measurement at a single microphone position. In terms of the number of transfer functions necessary to calculate a suitable average of the overall radiated sound energy of an instrument, measuring in reverberant acoustics means that a far smaller number is necessary than in an anechoic chamber. There is a danger that the room modes, which have a modal density (modes per frequency range) far higher than that of the instrument's modes, might cause trouble in a non-anechoic measurement by producing many additional peaks in the transfer functions. To avoid this, we adopt a simple procedure. For each fixed angle α_i between violin and microphone, the whole array (tripod including violin, impact hammer *and* microphone) is rotated through 36 different angles φ (0-360° at 10° increments), while the angle α_i between violin and microphone remains unchanged. In this way, 36 transfer functions for that specific angle α_i are measured and averaged (with respect to energy). This drastically reduces the influence of room modes on the desired transfer function (the measurement room is characterized by a volume of approx. 180 m3 and a reverberation time of approx. 0.6s). The distance between microphone (B&K 2237 SPM) and violin is 0.5 m, which is within the nearfield but far enough to be out of the immediate canceling effects caused by mode shape areas out of phase. The plane of the microphone rotation is perpendicular to the longitudinal axis of the violin at the position of the violin bridge.

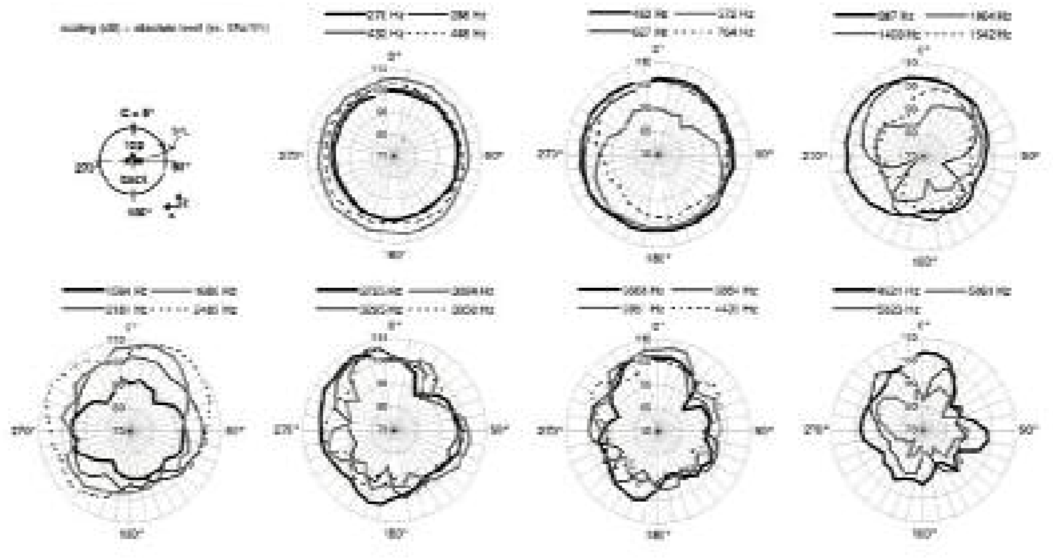
The result of this measurement is a 3D contour diagram of the radiated sound showing the absolute level of sound radiation

Figure 1.

A. Directional characteristics of sound radiation of a violin by Guarneri del Gesu, 1733. Sound radiation level L obtained by the ratio of sound pressure p divided by bridge force F as function of frequency f (x-axis) and radiation angle α around the instrument (y-axis) in the plane of the bridge at 36 different locations. $\alpha = 0° =$ microphone perpendicular to the top plate; $90° =$ bass side; $180° =$ perpendicular to the back plate; $270° =$ sound post side. Distance between microphone and violin 0.5 m. Levels L (dB, re 1Pa/1N) in absolute scaling: L/dB= grey legend value/dB + 80/dB. Note the monopole-like radiation of the (corpus-) resonances below 600 Hz and the increasing unevenness of the sound radiation field with increasing frequency.



B. Directional characteristics of sound radiation for some eigenfrequencies (data equal with fig. 1a). *Note*: Due to the measurement in nonanechoic (chamber music) environment the unevenness of directional radiation is smoothed. Note strong directivity.



$L_p(f;\alpha)$ as a function of direction α (y-axis) and frequency f (x-axis; see Fig. 1a). Horizontal grey-scale variations in the diagram indicate the frequency dependence of sound radiation in one particular direction, while vertical grey-scale variations indicate the directional dependence of sound radiation at a particular frequency. Almost omni-directional (monopole-like) radiation is seen below 1000 Hz, while increasingly complex radiation patterns become apparent as we move to higher frequencies, as expected [1]. Figure 1b, containing a subset of the data of Fig.1a, shows the directional dependence of sound radiation for the frequencies of various eigenmodes.

2. Energy-based averaging of the measured set of $L_p(f;\alpha)$ over all room directions α_i (with α=0-360° $\Delta\alpha$=10°). The result is called the *resonance profile* of the instrument (Fig. 2A-D).

3. The levels of the resonance profile are determined at the frequencies of all harmonics which belong to all playable chromatic tones of the instrument. As an input parameter, the vibrato shift is specified (in cents; 100 cent = 1 semitone). This determines the frequency interval at which each of the named levels is scanned. As a standard parameter here we usually use an "average" vibrato of 25 cents. With an overall vibrato shift of y cent the upper frequency limit h_i^+ (in Hz) of the ith vibrated harmonic h_i is given by

Ia) $h_i^+ = h_i{*}2^{(y/2400)} = i{*}f_0{*}2^{(y/2400)}$

where the frequency $h_i = i{*}f_0$, with f_0 being the fundamental frequency (in Hz). The corresponding lower frequency limit h_i^- is

Ib) $h_i^- = (h_i)^2/hi^+$.

The result of this step is a set of "harmonic levels". Some colored contour-maps of the harmonic levels can be seen in the sound radiation section of the website:

http://www.schleske.de/06geigenbauer/akustik3schall4musikdarst.shtml

Furthermore, comparisons between the harmonic levels of various violins (Stradivarius, Guarneri del Gesu, tonal copies) are given in the "Acoustical Handbook" of the website (Note: An English version of the web site should be available by Jan. 2003):

http://www.schleske.de/09extras/extras3handbuch03klangkopie.shtml

4. Multiplication of the *harmonic levels* by the following weighting functions:

a) Bow excitation: The harmonic levels are corrected corresponding to the relative strength of excitation of each harmonic from the force spectrum of a bowed string. A string vibrating in "Helmholtz motion" exerts a force on the violin bridge with a sawtooth waveform, which requires a weighting in which the nth harmonic is divided by n: relative to the fundamental, a factor of 1/2 for the second harmonic; 1/3 for the third harmonic etc. Correction factors for various types of strings can be included, to allow for waveforms which are not an ideal sawtooth.

b) Dynamic (pianissimo – mezzo forte – fortissimo): Adjustment of absolute harmonic levels according to a range of sound pressure values that would be produced by real bowing of the instrument (this calibration is necessary as the auditory filter functions of the inner ear depend on the absolute value of input levels.)

After applying these weighting functions to the measured harmonic levels, we have the spectral components that would occur if the instrument was bowed. In the following text and figures this part of the procedure (step 1-4) is called "bowed-calc." The weighted and calibrated harmonic levels are the input quantities for the next stage, the calculation of loudness.

5. Calculation of specific loudness (S) and overall loudness of all playable chromatic notes of the instrument.

Remarks on the term loudness: Loudness (measured in *sones*) is a psychophysical term describing the strength of the ear's perception of sound. The sone scale was created to provide a linear scale of loudness, which correlates with a listener's subjective judgment of loudness. For example, a sound of 2 sones is twice as loud as a sound of 1 sone, a sound of 4 sones is twice as loud as a sound of 2 sones, etc. The definition of the unit is that 1 sone corresponds to the loudness experienced by a normal person hearing a 1kHz (sinusoidal) tone at 40 dB SPL. The specific loudness S is the loudness per frequency bandwidth, specifically the loudness per *critical band* (a psychoacoustical frequency; see below). The distribution of specific loudness on this scale is an essential indication for the perception of tonal color. The overall loudness of a sound is obtained by summing this specific loudness across the whole scale.

Remarks on frequency scaling in ERB: The frequency scale in critical bands, expressed in ERB (Equivalent rectangular bandwidth of the filter characteristic of the ear), corresponds to the "frequency axis" of the human inner ear. Sound waves that reach the ear are transmitted through the eardrum and the three small bones of the middle ear to the cochlea, and set its basilar membrane (the basic mechanical sensor) into oscillation rather like a flapping flag. Around 30,000 receptor-units (hair cells) that are located on the basilar membrane [2] respond to the motion of the membrane and transduce this motion into a neural code in the auditory nerve. The "ERB-frequency-axis" in the psychoacoustical diagrams (Figs. 3-9) can be thought of as the unrolled basilar membrane of the inner ear. An interval of 1 ERB corresponds to the width of one *critical band*, and corresponds to about 0.9 mm on the basilar membrane (total length for adults, about 35 mm). A critical band characterizes the ear's ability to separate component tones, for example whether a loud tone can mask a nearby quiet one [3, 4]. For the perception of a complex stimulus (like a "musical tone") it is important to know whether frequency components lie within one critical band or if they are distributed over different critical bands. This difference plays a major role for various characteristics in our perception, like perception of tonal color, roughness, consonance or dissonance of musical intervals etc. [3].

The transformation from the physical unit "frequency" f (expressed in kHz) into the critical band number (expressed in ERB) is given by the following formula [4]:

II) Number of critical band = $21.4 \log_{10} (4.37f + 1)$.

Our loudness calculations are based on Moore, Glasberg et al. [4-7], by means of their program *loudaes* (using parameters free-field, diffuse, binaural, complex, and harmonic).

There are five steps:

a) Fixed filter for transfer from free field to eardrum

The outer ear (pinna and ear canal) forms a resonant acoustic system (basically a quarter-wave resonator), that provides approximately 0 dB gain at the ear drum below 1 kHz, rising to 15-20 dB gain in the vicinity of 2.5 kHz, and then falling in a complex pattern of resonances at higher frequencies.

b) Fixed filter for transfer through middle ear

The primary function of the middle ear is that of an impedance matching system, designed to ensure that the energy of the sound wave is transmitted smoothly with minimum reflections from the air in the outer ear to the fluid in the inner ear.

c) Transform spectrum to excitation pattern

The excitation pattern (descriptive as the vibration of hair cells) of a given sound is calculated from the effective spectrum reaching the cochlea. It is calculated from auditory filter shapes. The auditory filter shape represents frequency selectivity at a particular center frequency and can be thought of as a stimulus-dependent weighting function.

d) Transform excitation pattern to specific loudness S

The specific loudness is the loudness per critical band ERB.

e) Calculate overall loudness (alternatively in sone or phon) for each "musical tone"

The overall loudness of a given sound is assumed to be proportional to the total area under the specific loudness pattern S versus ERB.

Results:
Psychoacoustical diagrams showing

a) Specific loudness S of the instrument (in sone) as a function of a bowed-calc. musical scale (in semitones) and critical band (in ERB).

b) Overall loudness of the instrument (in phon) as a function of a bowed-calc. musical scale (in semitones).

The whole procedure can be summarized as follows: Steps 1-2 record the physical sound radiation of the instrument and represent it as a resonance profile. Steps 3-4 address the question: "In terms of the resonance profile, how strongly will certain spectral components be radiated when the instrument is bowed?" These steps help to interpret the resonance profiles of violins, violas and violoncelli in accordance with their playing condition, i.e. their musical relevance. Step 5 goes a little further as it treats the question: "What is the relevance of this radiation in terms of human perception?" This step interprets and scales the sound radiation according to the excitation of the basilar membrane and includes known effects of psychoacoustical processing of sound, like human hearing sensitivity and masking [7].

Example 1: Using the method for analyzing the radiation of a violin by Antonio Stradivarius (1712)

Figure 3 could be called a "tonal color (timbre) diagram". It shows the specific loudness that results from the measurements and calculations just described (for a description and eigenmodes of this Stradivarius see Part I, May 2002 issue). The top curve in Fig. 3 is the measured "resonance profile" of sound radiation (step 2) which gives the input data for calculating the specific loudness of all musical tones (steps 3-5) as they are represented in the grey-value diagram (middle). The darker the grey value, the higher the specific loudness and thus the more neural activity is caused by the respective bowed note (see vertical axis showing a chromatic scale with 60 semitones) at the respective location on the basilar membrane (see horizontal axis showing frequency group 2-37 in ERB). In these diagrams we decided instead of showing the plain specific loudness S, to represent "specific loudness levels LS" as defined by $LS = \log_2 S$. The consequence of this transformation is that a given linear *difference* of LS corresponds to an equivalent change of loudness

Figure 2.

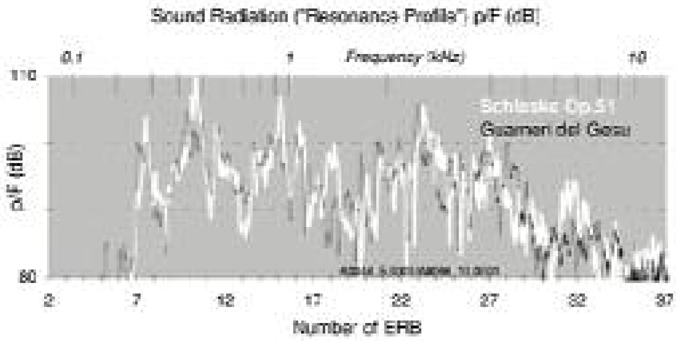
A. „Resonance Profile" of Guarneri del Gesu (black) and „Tonal Copy Op.51, 2001" (white).

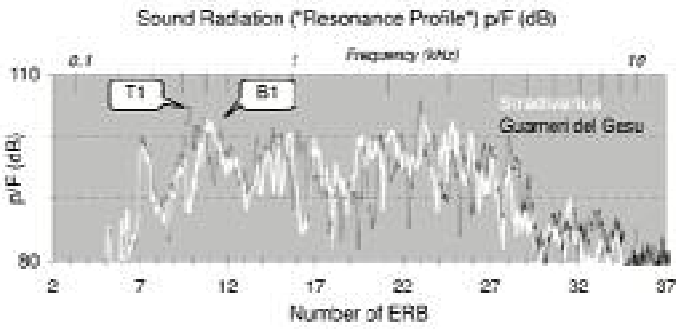
Typical similarities and differences become obvious:

- Similar characteristics of Corpus modes (eigenfrequencies, prominent levels). Typical for del Gesu: T1-Mode below 500 Hz has stronger radiation than B1 above 500 Hz.
- Similar incision between the resonances

Differences: The tonal copy shows stronger level variations; higher levels and more „brilliance-resonances" (around 32 ERB)

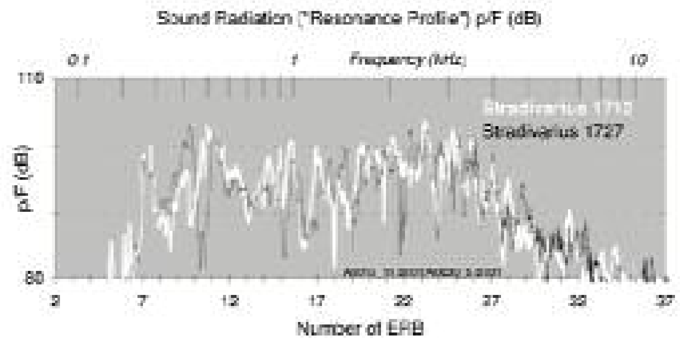
B. Comparison of „Resonance Profile" Stradivarius 1712 (white) versus Guarneri del Gesu 1733 (black). It shows the principle differences in „corpus resonance structure": Guarneri's T1 (433 Hz) and B1 (544 Hz) are far more apart from each other than those of the Stradivarius. Furthermore the T1 of Guarneri is the strongest radiating mode in the lower frequency range.





C. Comparison of „Resonance Profile" Stradivarius, 1712 (white) versus Stradivarius, 1727 (black). Note highly different resonance structure in the low-frequency corpus resonance region, but similar resonance structure from 1500 Hz upwards.

D. Comparison of „Resonance Profile" Stradivarius, 1712 (white) versus „Tonal Copy, 1999" (black). Note: Similar resonance structure in the corpus resonance region and in the general „covering" over the peaks. The "tonal copy" shows to have higher specific loudness at 28...32 ERB which we would regard as having more brilliance, focus and strength. Less loudness in that region on the other hand results in a smoother tone.



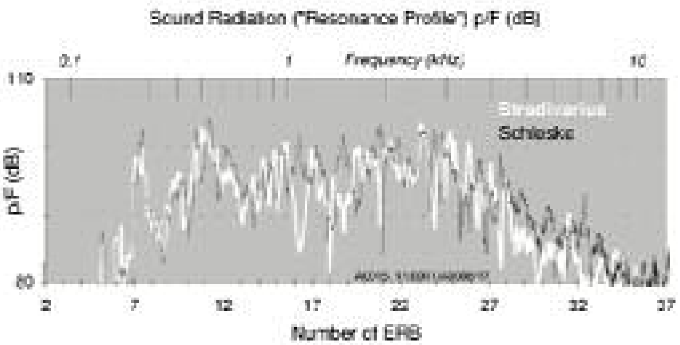


Figure 3. Psychoacoustic Evaluation of the sound radiation of a violin (*violin*: Stradivarius, 1712) – Demonstration of the steps and results of the method as described in the text:

On top: "Resonance Profile" of sound radiation (step 2).

Below right: Grey-Value-Diagram (contour plot) of the specific loudness as function of "musical tone" and number of ERB. Calculated from the Resonance Profile (step 3-5a). Vertical scale = chromatic scale of 60 musical semitones, starting with the open g-string as tone-#1- Horizontal grid lines represent musical fifths.

Horizontal axis = frequency, being scaled using a) "technical" frequency (Hz) (upper edge of Resonance Profile) and b) using the „frequency axis of the inner ear": number of ERB. Vertical grid lines represent each frequency group on the basilar membrane (number of ERB).

Note: The darker the grey values the stronger the excitation at this region on the basilar membrane caused by the respective "musical tone". Further explanations on this "timbre-diagram" see text.

Below left: Overall loudness level (in phon) as function of musical tone. It results from the summing across the specific loudness-values of all frequency groups (step 5b).

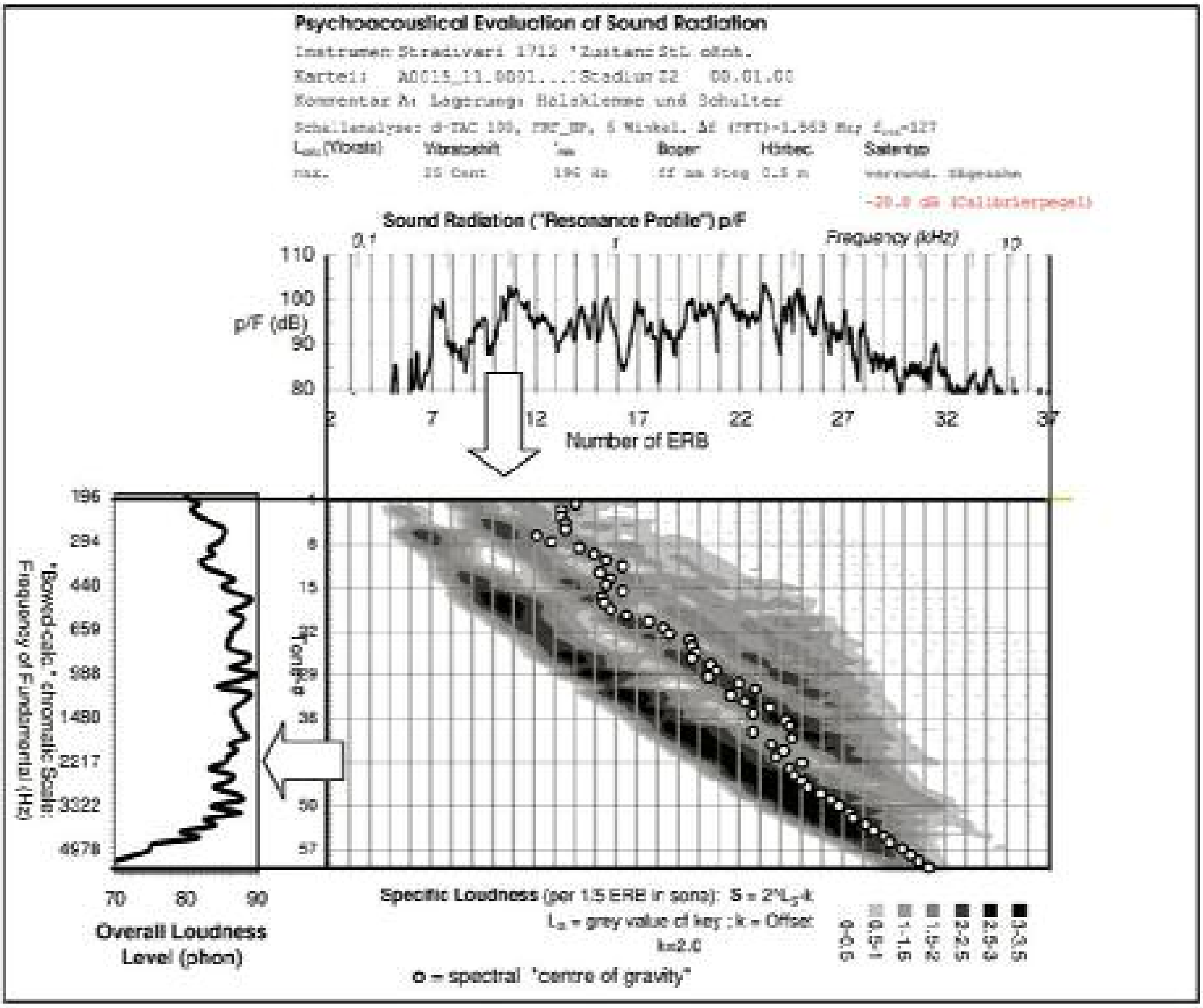


Figure 4. Psychoacoustical differences between the Stradivarius, 1712 and a Guarneri del Gesu, 1733. The diagram represents the differences of specific loudness-level [$\Delta LS = \log_2(S_A/S_B)$ with S_A being the specific loudness of Instrument A, S_B being the specific loudness of Instrument B] as function of the „bowed-calc. musical tone" (vertical axis) and the number of ERB (horizontal axis).

Note: A difference of $\Delta LS = 1$ (s. key) represents twice the specific loudness. White areas of a certain note show the amount to which the „white instrument" (here: Stradivarius) causes higher specific loudness at this particular region on the basilar membrane as compared with the „black" instrument (here: Guarneri). Analogous is true for the black areas: Here Guarneri creates higher specific loudness than Stradivarius. So the diagram from tone to tone shows a psychoacoustic comparison of timbre as it visualises to which amount the different instruments excite different parts of the inner ear.

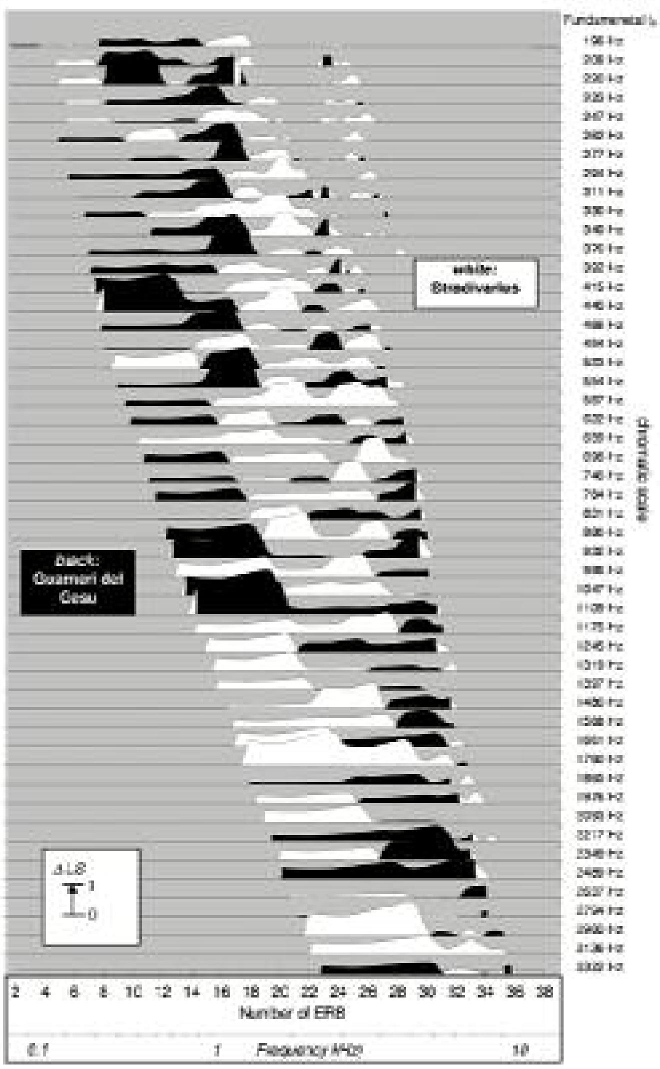


Figure 5. Specific loudness variations as function of musical tone (vertical scale) and number of ERB (horizontal scale) caused by playing each tone of the chromatic scale with a 25-cent vibrato. It shows that the variations in different frequency groups and for different tones are relatively unequal. The diagram shows to which extent the vibrato allows to modulate not only loudness but timbre of the violin. Instrument: Guarneri del Gesu, 1733. Calculation not from the real bowed string but from "Resonance Profile" using steps 1-6 (see text). See fig. 4 for explanation.

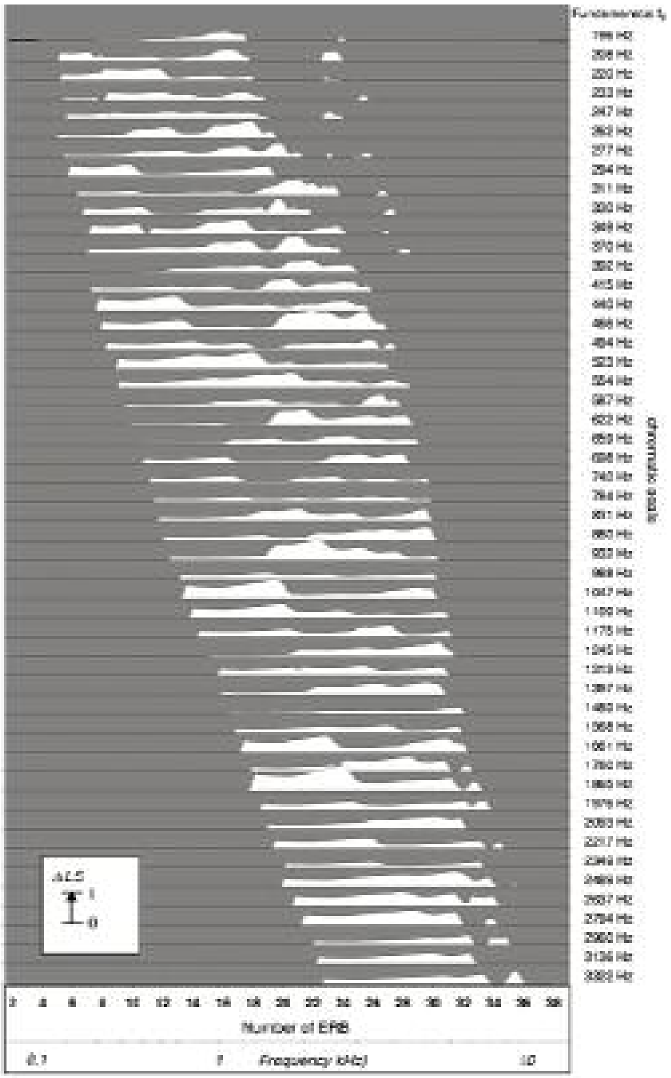


Table 1.

Sound	Specific Loudness S (in sone)	Specific "Loudness Level LS" $LS = \log_2 S$ (as used in our topographic contour diagrams)	Perceived loudness-change
#1	1	0	
#2	2	1	= twice #1
#3	4	2	= twice #2
#4	8	3	= twice #3
#5	16	4	= twice #4

perception that is particularly helpful when dealing with this sort of topographic-style maps: each grey-value *change* represents an equal change of perception if L*S* instead of *S* is plotted (see table 1).

The specific loudness levels around the musical tone's fundamentals are located on the first (from left) diagonal bent grid line. The respective diagonal grid lines that follow adjacent on the right-hand side give the positions of the specific loudness levels that are caused by the following harmonics. Furthermore a white data point for each musical tone in the grey-value diagram represents the position of the tone's "spectral center of gravity": the sums of specific loudness *S* across the critical bands above and below that point are equal. The "spectral center of gravity" gives an indication of the tonal color, "dark" versus "bright": the nearer this point is to the left-hand side, the more the sound of that musical tone tends to be "sonorous" or "dark".

It should be noted that Fig. 3 shows which resonances of the instrument are responsible for causing the various regions of "concentrated" specific loudness of musical tones. Thus the degree of importance of various resonances in the resonance profile can be interpreted. Moving from the Stradivari's strong corpus resonances (see resonance profile around 500 Hz, respectively 10-12 ERB) vertically downwards into the grey-value contour diagram we find the "concentrated" specific loudness in the region of the fundamentals of the lower part of the A-string (tone# 15-20), giving those tones "strength" and "depth". Changes of tonal color ("timbre") from tone to tone are made evident by the vertical change of grey-value structure along the chromatic scale. The G-string notes start with only little specific loudness at the region of their fundamentals, followed by a clear timbre change around tone #7 (#C). Here the effective radiation caused by the Helmholtz resonance A_0 causes a strong increase of "fundamental loudness" around 7-8 ERB.

Comparing G- and D-string with A- and E-string, a significant weakness of violins in general becomes obvious. Compared with the higher strings the lower strings lack excitation potential in the region where their fundamentals excite the basilar membrane. Due to the comparative human deafness in the low frequency region and due to the existence of only one single useful resonance (the Helmholtz resonance A_0) in the region of the first octave, the violin sounds comparatively bright in the lower range compared with the timbre of the A- and E-strings. In agreement with this, the lower strings show centers of spectral gravity shifted to rather high ERB-values relative to their fundamental frequencies (on the G-string around 14 ERB, on the D-string around 16 ERB). Only from the open A-string upwards do the fundamentals start to benefit clearly from the resonance strength of the corpus resonances (T1 and B1) and the centers of spectral gravity of the respective musical tones (#19...) start to move rather steadily upwards with increasing pitch. For this Stradivarius, from the open A-string (tone #22) up to #F^3 (tone #36) the centers of spectral gravity are relatively constant around the frequency of the respective 2nd harmonic. For higher musical tones on the E-string the centers of spectral gravity start to shift downwards. Due to the low-pass filtering effect of the violin's bridge which progressively affects the lower harmonics of musical tones, the specific loudness of these high musical tones on the E-string above tone #36 are increasingly dominated by the strength of their fundamentals.

The curve in the left part of Fig. 3 shows the overall loudness-level (in phon) as a function of the chromatic scale. The overall loudness of each of the musical tones results from "horizontally" summing the specific loudness across all frequency groups. The maximum spread of overall loudness-level, an important indicator of the dynamic balance of the instrument, is about 10 phon. Also here we see that the "acoustical potential" clearly decreases from the higher strings to the lower ones, which "challenges" the player to balance. This challenge (to avoid the term weakness) is even stronger in the violoncello.

PSYCHOACOUSTIC COMPARISONS

As a final step of our method it has proved valuable not only to analyze the specific loudness of a single instrument but also to calculate the differences between two instruments. It has been found that even when using a high resolution color scale for plotting absolute loudness patterns, the visual appearance of specific loudness pattern diagrams of different sounding violins look almost the same. Obviously our eye is poor at perceiving and weighting such small differences, but our ears are more acute. My impression has been that our sense of hearing seems to perceive even the smallest changes in tonal color when listening to different sounds, whereas our visual sense almost seems to ignore those differences on the respective colored loudness diagrams. Only if colored maps are created that visualize the loudness *differences* of instruments instead of visualizing their *absolute* loudness patterns do the tonal differences seem to correspond with the visual representations. This finding led to the last step:

6. AB-comparison of two instruments

   a) Difference of the specific loudness levels $LS" = \log_2 S$ of two instruments A and B. *Result*: Psychoacoustic differences of

Figure 6. Stradivari did not copy himself: Psychoacoustical differences between the Stradivarius, 1712 (white) and Stradivarius, 1727 (black) caused by differences in the resonance structure (see fig. 2c). High similarity in specific loudness above 18 ERB. (see fig. 4 for explanation)

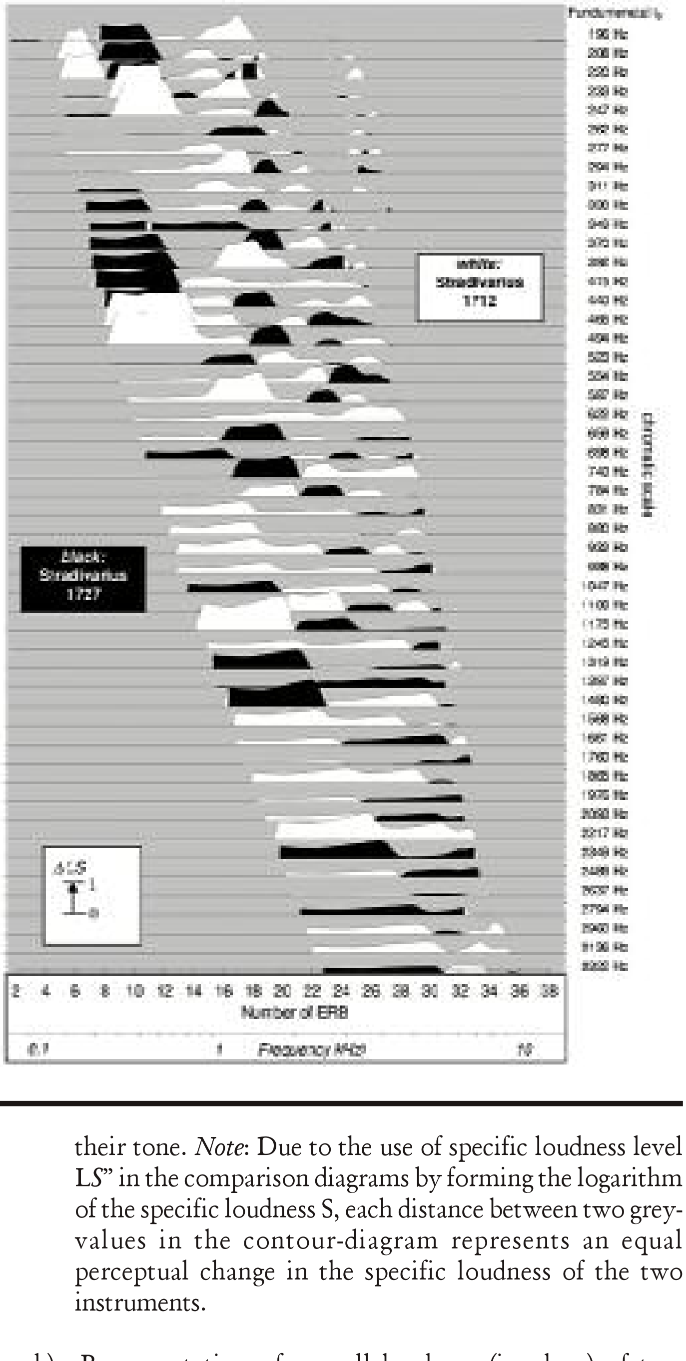
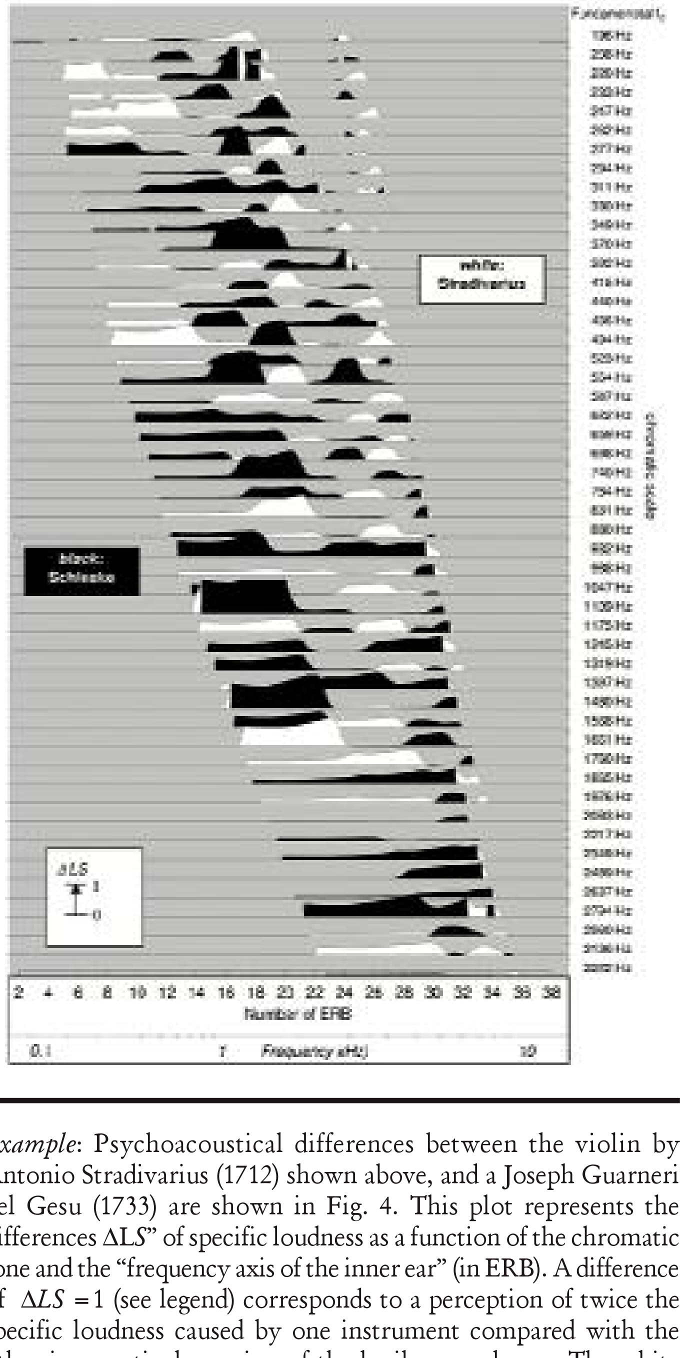


Figure 7. Psychoacoustical differences between the Stradivarius, 1712 (white) and Schleske, 1999 (black). Higher specific loudness (particularly between 16-24 ERB) of the new instrument (see fig. 4 for explanation).



their tone. *Note*: Due to the use of specific loudness level LS'' in the comparison diagrams by forming the logarithm of the specific loudness S, each distance between two grey-values in the contour-diagram represents an equal perceptual change in the specific loudness of the two instruments.

b) Representation of overall loudness (in phon) of two instruments A and B (see Fig. 10a-c)

Example: Psychoacoustical differences between the violin by Antonio Stradivarius (1712) shown above, and a Joseph Guarneri del Gesu (1733) are shown in Fig. 4. This plot represents the differences $\Delta LS''$ of specific loudness as a function of the chromatic tone and the "frequency axis of the inner ear" (in ERB). A difference of $\Delta LS = 1$ (see legend) corresponds to a perception of twice the specific loudness caused by one instrument compared with the other in a particular region of the basilar membrane. The white areas in the diagram show the regions and the amounts of higher specific loudness of the "white" instrument (the Stradivarius) compared with the "black" instrument (the Guarneri del Gesu). The horizontal scale reveals where on the basilar membrane these different levels of excitation occur. The corresponding is true for the black areas, showing where the "black" instrument has higher loudness. So this diagram gives a psychoacoustic comparison-tool for visualizing tonal color from tone to tone (Note: For a colored version of this diagram see http://www.schleske.de/picshoch/a0015_vgl_a0044_abstr_psy.gif).

AB-comparisons of different pairs of masters can be done, based on a database of some 40 violins analyzed using the above techniques. In contrast to other masters the comparison of Stradivarius versus del Gesu might reveal *typological* differences, since the following difference-*pattern* can be observed (more violins by these two famous masters should be analyzed and compared before strict conclusions can be drawn): The del Gesu causes a relatively strong "firing" of nerves in the lower (sonorous) ERB-region (8-20 ERB) and at the same time in the higher (brilliance) ERB-region (27-32 ERB), while the Stradivarius causes stronger excitations in the intermediate region of the basilar membrane. For very high musical tones (from about one octave above the open E-string) the Stradivarius has a more fundamental-dominated sound: from D^3 (1175 Hz) on, the calc-bowed tones create stronger specific loudness in the fundamental region of each tone (left region of white areas) compared to those of the Guarneri del Gesu. Despite these differences that can clearly be perceived as different tonal colors when listening to both instruments, their calculated overall loudness (as an indicator of the "dynamical reserves" of each instrument) is almost identical (this follows from Fig. 10a). Furthermore, both violins show a comparable degree of fluctuations of overall loudness going through the chromatic scale from tone to tone. As mentioned above these fluctuations are in the range of 10 phon which corresponds to a doubling of loudness perception. They are an indication of the degree of "dynamic imbalance" of the instruments, for which the player must compensate.

Comparisons made with the aid of these psychoacoustic diagrams prove to be a discriminating empirical tool

- when investigating tonal color differences of various instruments
- when controlling the sound of newly made instruments
- when performing parameter studies on the tonal influences of certain construction parameters or adjustments of the instrument.

Recall that these results are based on the data of the measured resonance profiles of the instruments (step 1) and the ensuing calculations (steps 2-5), not on the subjectively real bowed instrument. The method tries to extract musically relevant information ("harmonic levels") and psychoacoustically relevant information ("excitation of the basilar membrane") from the "technical" data of the resonance profiles of the instruments and thus suggests how the specific resonance profile could be interpreted. Nevertheless some limitations (that may have noticeable effects on our perception of sound) should not be overlooked:

- The hammer-excitation of the instrument (step 1) is performed only in the main excitation direction of the bow (perpendicular to the string)
- All phase information of the radiated sound is lost (due to averaging out the room modes)
- All spatial information of the radiated sound (still present in step 1) is lost with the further steps (due to energetic averaging across the radiation angles in order to calculate a resonance profile as input for the following psychoacoustic evaluation)
- No time-varying effects are taken into account.

WHY ACOUSTICAL TOOLS?

Together with Part I (concentrating on construction and modal analysis), our acoustical workshop tools have now been described. We would like to end this introduction with some examples of the benefit of their use. In terms of workshop practice we would state that acoustical tools can be helpful for

A) Learning to understand correlations between construction and sound
B) Learning to evaluate parameter studies
C) Learning to control the making process of new instruments
D) Learning to diagnose faults and weaknesses of instruments (because of length limitations for this paper, this last point must be kept for a later publication)

A) Understanding correlations – Example: resonance profile and the effectiveness of the player's vibrato

Each serious violin maker tries to learn which controllable parameters in the making process of a violin are responsible for certain tonal attributes. This section focuses on a "triad" which is particularly important for the musical success of a violin: the harmony of construction parameters *(here: violin varnish)*, the acoustical relevance *(here: resonance damping)* and musical perception *(here: vibrato and modulability):*

When the resonance profile of an instrument shows significant level differences in narrow frequency bands, vibrato from the player (which causes a periodic change of pitches of all harmonics of the played tone due to the oscillating motion of the left hand) will create a distinct *amplitude* modulation of the harmonics. To achieve significant level differences between narrow frequency bands requires a reasonable density of resonances per frequency range and low damping values of the single resonances, leading to a low "modal overlap factor" [8]. When there are significant narrow-band level differences in the resonance profile, the small periodic

Figure 8. The specific loudness differences between a Guarneri-Copy and a Stradivari-Copy are very similar to those between the two original instruments (compare with Fig. 4).

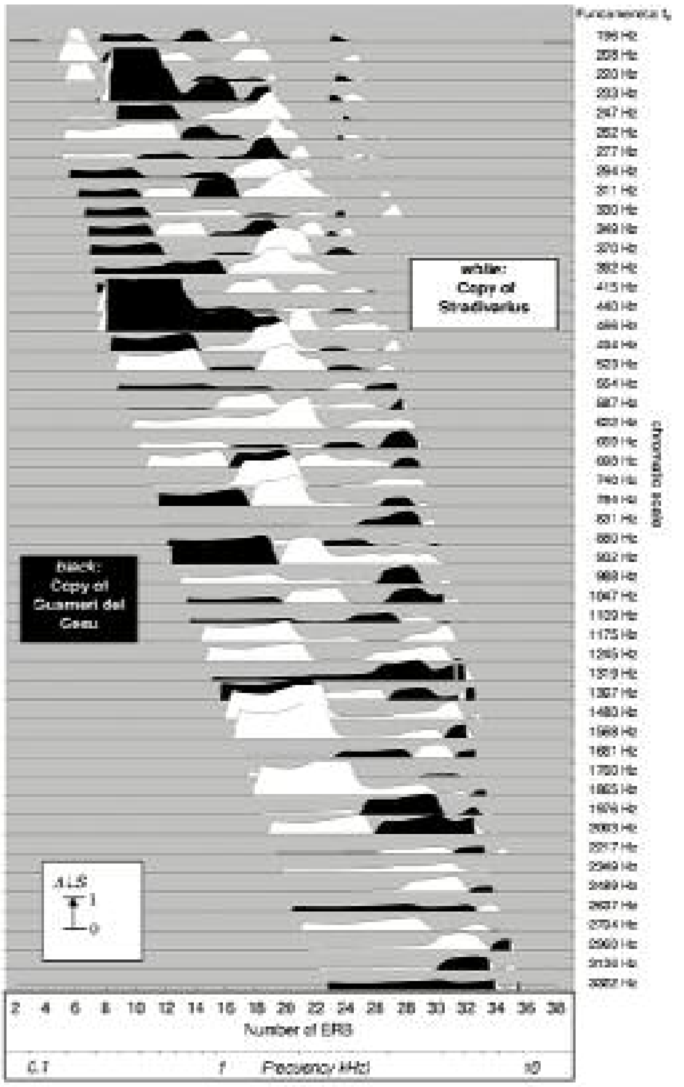
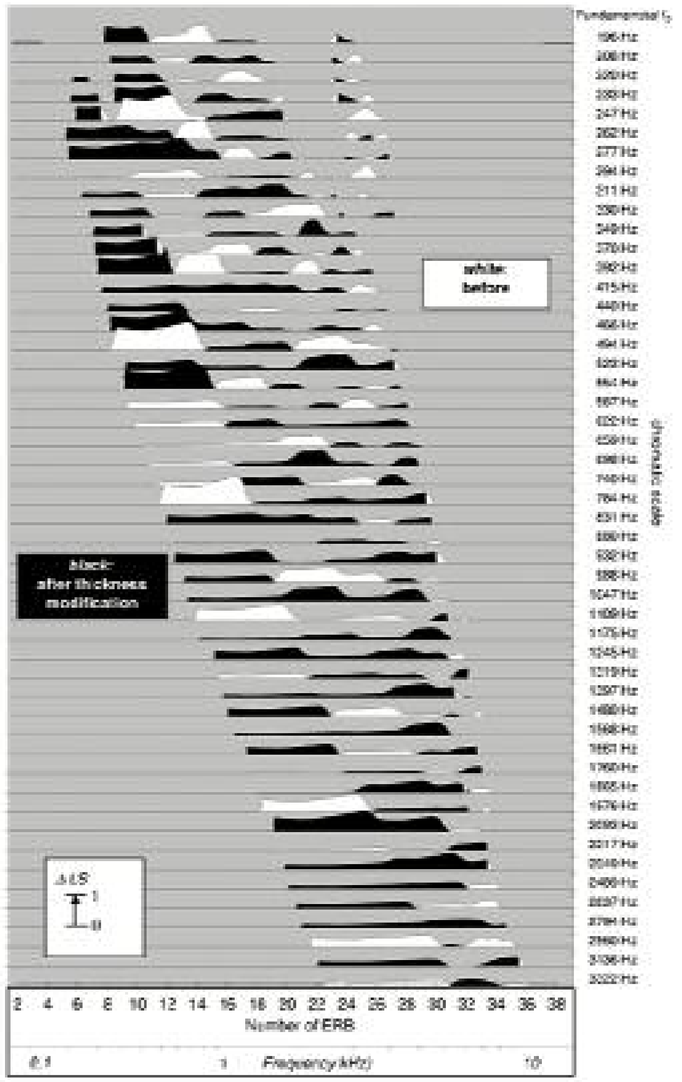


Figure 9. Effect of thickness modification (see Fig. 14) on specific loudness pattern. It shows: You can not win everything. But in most regions (black areas) the dynamic resources could be developed. (see Fig. 4 for explanation)



frequency shift from vibrato is sufficient to make the harmonics of the played tone rush up and down over the (fixed) resonance peaks of the instrument. The work of Gough [9] and, back in the 1970's, McIntyre and Woodhouse [10] has considered this "vibrato effect", and aimed "toward a psychoacoustically realistic violin physics". The latter work arose out of the experiments by Max Mathews with electronically simulated violin resonances. Similar psychoacoustical experiments by Weinreich [11] using electronic synthesis showed that purely frequency-modulated vibrato was perceived as sounding synthetic or vulgar, whereas a pure amplitude modulation of harmonics (with the frequency-modulation artificially removed) was perceived as almost unchanged, as compared with a natural real vibrato.

In our opinion a reason for this phenomenon might be based on the fact that a pure frequency modulation only causes a periodic local *shift* of the unchanged excitation pattern on the basilar membrane, whereas an amplitude modulation leads to a periodic change of excitation pattern *shape*. This change of shape would be due to a) periodic changes of the overall area of the excitation pattern, and b) the nonlinear fanning out of the upper flanks of auditory filter functions with increasing levels [4]. It can be assumed that such periodic changes of excitation pattern shape give rise to more complex neural signals to the brain than simple periodic frequency shifts of excitation patterns. It is well known that fluctuations or changes in all kinds of sensory stimulation create higher attention than constant stimuli, even when being of high intensity.

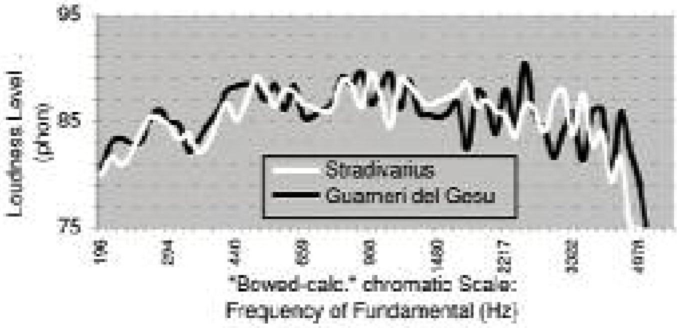
For the quality of the instrument this means: the higher the resonance density and the less damped the resonances of the violin, the smaller the variations in the playing of the instrument (vibrato; change of bowing parameters etc.) which will affect the neural excitation level and will thus increase the noticeability of the sound. It can be presumed that the “fieriness” and “liveliness” in the tone of high quality violins is (besides other things) based on such an effect. This effect might have to do with what workshop experience may call *“perception by quality”* in contrast to a pure “*perception by intensity”* when judging violins.

Example: As described above, the minimum and maximum sound pressure levels of the harmonics of a musical tone during one vibrato period cause different excitation patterns on the basilar membrane and thus different specific loudness. For a typical musical tone (A^1; 440 Hz fundamental frequency) Fig. 11 shows the maximum (black curve) and the minimum (grey curve) specific loudness as they are created by the sound pressure levels of the harmonics during one vibrato period (medium vibrato with an overall shift of 25 cent). Levels are “calc-bowed” according the method described earlier. The instrument used is the Joseph Guarneri del Gesu 1733 violin (see Fig. 4). The sound pressure (dB) showing the maximum levels of harmonics is indicated on the left scale, while the specific loudness curves (sone) corresponding to the maximum and minimum levels are indicated on the right scale. There are very obvious differences in specific loudness curves caused by vibrato (or more precisely by the amplitude modulation of the vibrated harmonics). These differences are particularly distinctive in the region of the fundamental (10 ERB) which for this particular violin is due to its strongly radiating T_1 corpus mode in the immediate neighborhood of the fundamental frequency of that tone.

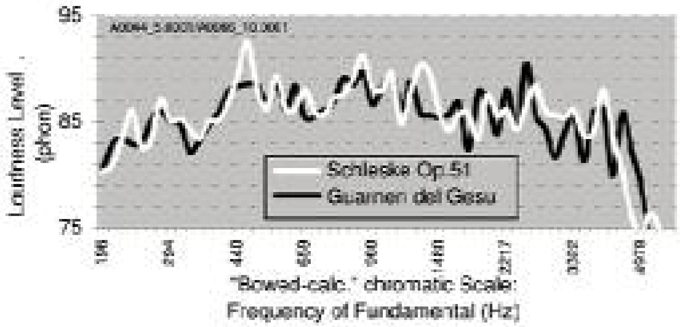
Through each vibrato period of the bowed musical tone the specific loudness changes periodically between the two curves shown. However, the individual harmonics do not evoke their minimum and maximum values simultaneously, but normally at different times. The reason for that is that each “vibrated” harmonic is shifted along the frequency axis (in a local frequency range determined by the degree of vibrato shift) and thus each harmonic moves up and down over the resonance profile of the instrument and reaches its local level-maximum and local level-minimum at different times. So, for each harmonic its spectral proportion of maximum and minimum sound pressure per vibrato period is radiated at different times. As a consequence the local maxima and minima on the basilar membrane are not created synchronously. In other words the motion from maximum to minimum loudness pattern and back within one

Figure 10. Comparing overall loudness (calculated as described in steps 2-5) as function of „musical tone” of various violins – showing the „dynamic resources” of the instruments:

A. Stradivarius, 1712 (white) and Guarneri del Gesu, 1733 (black)



B. Guarneri del Gesu, 1733 (black) and Schleske, Op.51, 2001 (white)



C. Stradivarius, 1712 (white) and Schleske, Op.37, 1999 (black)

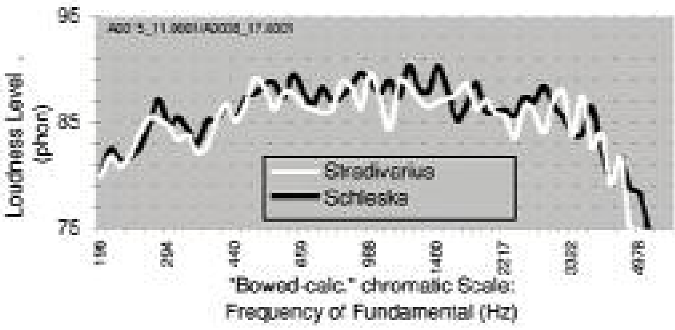
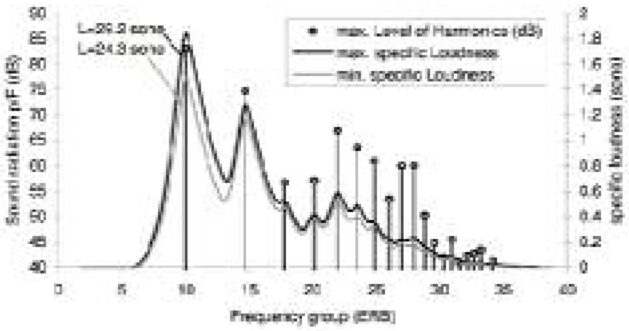


Figure 11. The figure shows the effect of the amplitude modulation of harmonics caused by the player's vibrato: It creates a periodically differing excitation of the basilar membrane. Maximum (black curve) and minimum (grey curve) specific loudness pattern during a vibrato period (vibrato frequency shift: 25-cent; tone; a1; Instrument: Guarneri del Gesu, 1733. The Sound-levels of the harmonics (belonging to that tone) that create the maximum pattern are represented by data-points. Calculation not from the real bowed string but from "Resonance Profile" using steps 1-6 (see text).



vibrato period does not happen in phase but (depending on the characteristics of the resonance profile) with significant phase differences. It can be guessed that this effect may intensify the "liveliness" of the perceived musical tone, since with these non-simultaneous effects the neural processor presumably is kept busier evaluating the neural code than with a uniform change of specific loudness. Only if all harmonics reached their local maximum in the resonance profile at the same time would the vibrato-caused modulation of overall loudness for this example (with unchanging bow dynamics) vary between L=29.2 sone and L=24.3 sone as indicated in the figure. Effects of time-masking are not considered here. Both the fluctuation of overall loudness caused by the vibrato and also the local fluctuations of specific loudness could be important for the perception of the "liveliness" of a musical tone – for some critical bands and tones, as shown in Fig.5, these specific fluctuations reach a factor of two! The amount by which the specific and overall loudness of a musical tone is modulated within one vibrato period depends on the quality of the instrument's resonance profile in the region of the harmonics belonging to that tone.

In order to investigate this quality Fig. 5 shows the differences of specific loudness for all playable musical tones (vertical axis: chromatic scale) caused by the vibrato (same vibrato and same instrument as in Fig. 11). The heights of white areas represent the difference of specific loudness level $\Delta LS = \log_2(S_{max}/S_{min})$ where S_{max} is the specific loudness caused by the maximum levels of harmonics and S_{min} is the specific loudness caused by minimum levels of harmonics during one vibrato period. A difference of $\Delta LS = 1$ (see legend) corresponds to a perception of doubling the specific loudness.

The diagram shows that over the whole playing range the maximum fluctuations of specific loudness caused by the vibrato are considerable. It is obvious that these fluctuations are significantly different in different critical bands. The fluctuations show a slight tendency towards higher magnitudes at higher critical bands. As the fluctuations are not equally distributed over the ERB-scale it is obvious that not only the overall loudness but also the tonal color (timbre) is modulated by the vibrato. As can be seen, this musical attribute, which one might call "modulation", is not equally pronounced for all musical tones. The differences in shape and size of white areas show that the musical tones are far from reacting with uniform sensitivity to the vibrato of the player. Some tones react more sensitively (i.e. create more excitation pattern changes per given "playing change") than others. It can be presumed that these processes (namely an invariable resonance profile and frequency-variable vibrated harmonics) demand highly complex processing activities of the human sense of hearing, occupying the neural processor. The testimony of musical listeners who "feel thrilled" by such "lively violin tones" might be based on the effects described.

In terms of the quality of the resonance profile, the account developed here emphasizes the importance of a high resonance density and small resonance damping values in order to increase the modulabilty of the instrument. This underscores our statement (see Part I) about "musical violin varnish" concerning the target of achieving low damping of eigenmodes and an increase of the wood-quality-ratio c/δ (with c = speed of sound of longitudinal waves; δ = density).

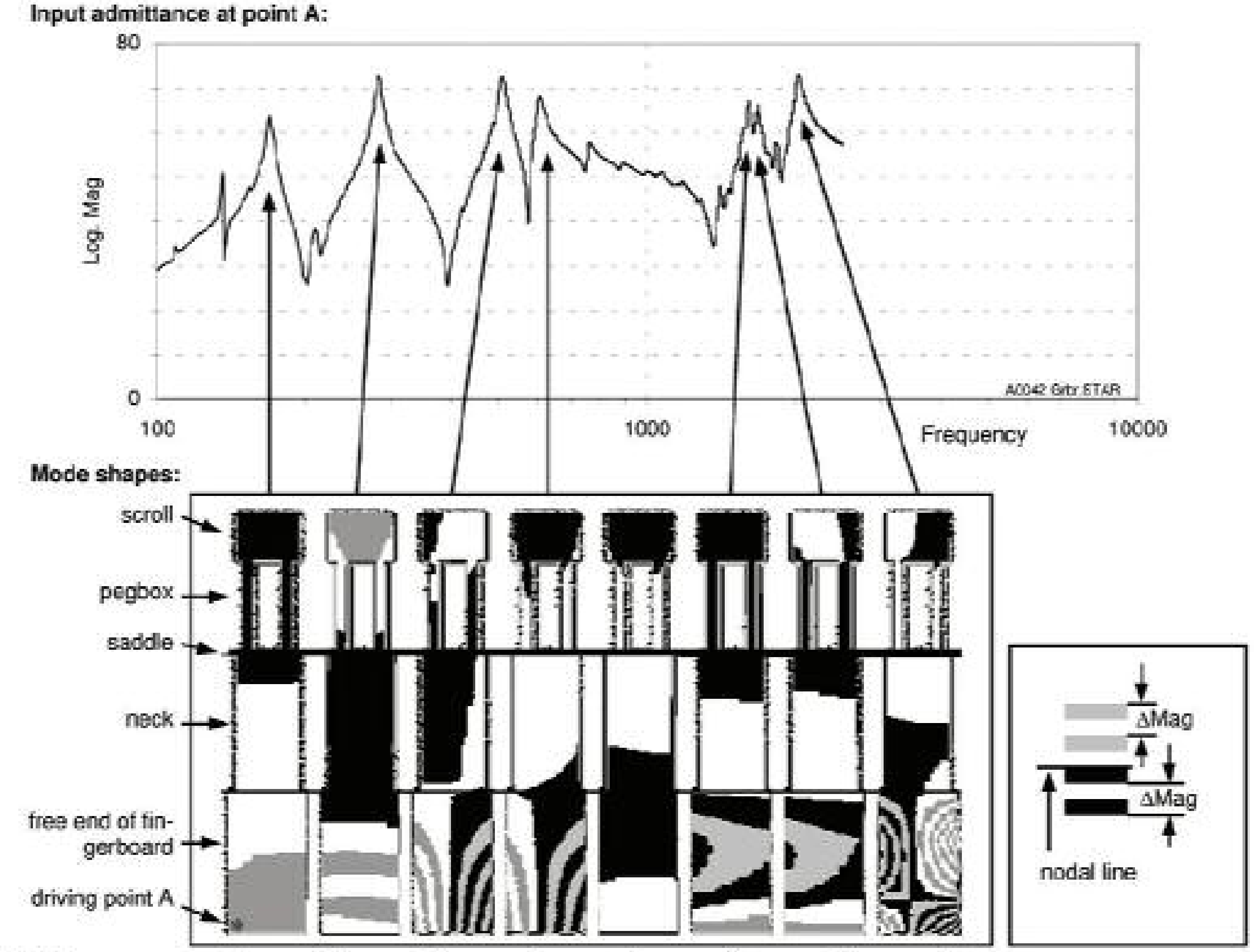
With regard to their experiments on electronically simulated violin resonances" [10] Woodhouse points out [12] that "if the damping is *too* light the result becomes unpleasant again. The reason seems to be that the high-Q resonances are still ringing on at their *own* frequency when the pitch of the vibrato note has shifted significantly away, and the resulting composite sound has discordant ingredients"(Note: Q is defined as the ratio of resonance frequency divided by half power bandwidth; Q is the inverse of loss factor η, or the inverse of twice the damping). This raises the potential danger of damping becoming too low, but Woodhouse admits that although the damping values of conventional instruments may come close to such a ringing situation their resonances do not seem to reach such low damping. So it should be safe to say (unless a violin is made of a material other than wood) that the aim of using any treatments (wood pre-treatment, primer, varnish, etc.) is to create a resonance profile with the lowest possible damping values and the highest possible resonance density.

In view of the fact that the density of violin resonances as a function of frequency (in Hz) is approximately constant whereas the frequency shift of each harmonic caused by vibrato increases with harmonic number, the effect described should become more noticeable in the higher frequency range of the resonance profile.

Figure 12. Eigenmodes of the fingerboard being mounted on the violin.

On top: Input admittance at driving point A (free fingerboard corner) showing the resonance peaks.

Below: Mode-shapes belonging to those peaks (experimental Modal Analysis).



Mode:	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Frequency (Hz)	**170 Hz**	**283 Hz**	**507 Hz**	**603 Hz**	**759 Hz**	**1620 Hz**	**1680 Hz**	**2030 Hz**
Damping	1.0 %	1.0 %	1.3 %	1.6 %	1.0 %	1.1 %	1.1 %	1.5 %
max. Mag. (v/F)	1.9E+01	1.7E+01	1.4E+02	1.2E+02	6.1E+00	4.6E+01	3.9E+01	1.9E+02
min. Mag. (v/F)	-3.6E+01	- 9.5E+01	- 1.1E+02	- 7.6E+01	- 1.4E+01	-4.0E+01	-3.8E+01	-2.2E+02

The shown mode-shapes result from the residues of the Frequency Response Functions (FRF); with FRF=v(f)/F(f) (admittance).

The higher the harmonic number, the wider is the absolute frequency shift (in Hz) by which that harmonic fluctuates over the violin's resonances and the higher is the number of resonance peaks of the instrument that are "crossed" by that harmonic within one vibrato period. Fig. 5 shows the maximum differences of specific loudness during one vibrato period but not the locally different *frequency* of fluctuations within that period. The increasing resonance density relative to the frequency shift of each harmonic is the reason why this fluctuation increases with increasing harmonic number. There is also a spatial effect. Each resonance peak of the instrument is characterized by its own "radiativity" [1]. The vibrato on a fine violin (fulfilling the criteria described above) is not only characterized by an amplitude modulation but also by a "radiativity modulation" – a modulation of spatial radiation which is more noticeable when more resonance peaks are crossed by the harmonics of the vibrated tone. This might be the reason why musicians sometimes claim that the tone of a fine violin "lives" in the hall or has some kind of "spatial authority". These considerations emphasize the importance of the higher frequency range of the resonance profile for the modulability of the instrument.

Note: The modulabilty diagram Fig. 5 must not be confused with the AB-comparison diagram Fig. 4. While the modulabilty diagram compares the differences of maximum and minimum specific loudness caused by the vibrato on one instrument, the AB-comparison diagram compares the maximum specific loudness (within a certain allowed vibrato shift) between both instruments.

B) Parameter studies – Example: Acoustics of the Fingerboard

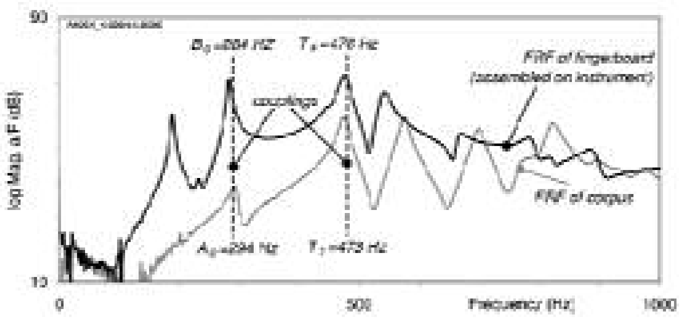
From Part I of this paper (table 3) it can be seen that two violins by Antonio Stradivarius happen to show two frequencies of the B1-mode in the resonance profile. The eigenmode-map of the "Schreiber"-Stradivarius 1712 given in Fig. 14b of Part I indicates that indeed two modes (at 513 Hz and closely above at 524 Hz) show the typical B_1 mode-shape. The difference between these modes lies in the fact that they show opposite phases between the free end of the fingerboard (twisting around its longitudinal axis) and the top plate. This obviously indicates a resonant coupling between the "corpus system" and the "fingerboard subsystem". Modal analysis of the glued-on fingerboard indeed shows a number of fingerboard modes that act largely independently from the modes of the corpus. Fig. 12 shows the resonance peaks of these fingerboard modes in the input admittance (measured at driving point "A" at the left corner of the free fingerboard end) and below that the mode shapes corresponding to these peaks. In the frequency range up to 2500 Hz the fingerboard subsystem shows eight modes, where mode #2 is a bending mode of the free end ("B0-mode"); mode #3 and #4 are torsional modes ("T_f-modes") of the free end; mode #6 and #7 high frequency bending modes with nodal lines already within the free fingerboard's end and finally mode #8 a torsional mode with a nodal line cross within the free end.

Investigations on adjusting violins with new fingerboards in our studio showed that with a carefully graduated fingerboard it is possible to create a coupling of one of the torsional modes T_f of the fingerboard (modes #3 or #4 in Fig. 12) with one of the corpus modes, especially with the B_1-mode. What follows from that is a "spectral splitting" of that corpus mode. As this splitting causes a "widening" of the frequency region of significant radiation from the corpus modes (see Fig. 14a of Part I, May 2002 issue) by transforming one well radiating mode into two well radiating (adjacent) modes, this effect is probably desirable. It will be particularly noticeable in the region of the first position of the G- and A-strings, where the second harmonics (G-string) and fundamentals (A-string) fall in that frequency region.

More familiar is the so-called A_0-B_0 coupling. In this case (also present in the violins by Stradivarius shown in Part I) mode #2 (Fig. 12), here at 283 Hz, couples with the Helmholtz mode A_0. The mechanism of A_0-B_0 coupling is described in detail by Woodhouse [13]. From our workshop practice we have observed that "resonance-coupled" instruments (with A_0-B_0 coupling and preferably also T_f coupling) are regarded by most players as being more "lively" or "resonant". We share this judgment with Hutchins [14] and Woodhouse [13].

An example of a fingerboard made in such as way as to give both T_f coupling and A_0-B_0 coupling is shown in the frequency response curves (acceleration a divided by force F) in Fig. 13. The black curve is a transfer function between the two corners of the free end of the fingerboard (glued in place on the violin). For this measurement of fingerboard modes the ff-holes are covered with foam in order to damp the A_0-mode and minimize coupling, to isolate the real eigenfrequency of mode #2 ("B_0"). The grey curve is an input accelerance (a/F) of the corpus (driving point at the left

Figure 13. Example of a successful coupling of fingerboard modes with corpus modes. Black: Frequency Response Function (FRF) of fingerboard; grey: FRF of corpus. There occur two couplings; A_0-B_0 and T_F-T_1 and the instrument is well adjusted to perform a more „lively" and „resonant" feeling.



bridge foot). For this measurement the free fingerboard end was held tightly with one hand in order to avoid coupling with the B_0 and T_f modes, so that the real eigenfrequency of the Helmholtz mode (A_0) could be determined. The figure shows that two close matches of eigenfrequencies have been achieved (vertical broken lines): (a) Helmholtz mode (A_0) with corpus mode (B_0), and (b) fingerboard torsion (T_f) with the lower corpus mode (T_1). This fingerboard is well tuned to give a twofold coupling with the corpus of the instrument. In our experience this gives the instrument a "living" and "resonant" feeling when being played.

Tuning the fingerboard:

In order to achieve the best tuning of the fingerboard for a given instrument we have determined some empirical workshop rules. The mode shape of the first bending mode ("xylophone mode") of the fingerboard under free boundary conditions is somewhat similar to how the fingerboard will vibrate in the B_0 mode when it is glued on the violin. To hear this xylophone mode frequency, hold the free fingerboard at one of its nodal lines at approximately 1/4 of its length and tap and listen at one end or the centre. In the case of our newly made violins (which have relatively similar scrolls and necks) the eigenfrequency of this free fingerboard mode turns out to fall at 1.67-1.68 times the eigenfrequency of the eventual B_0 mode. As this frequency ratio is almost a major sixth, the free fingerboard should thus be tuned to that interval above the frequency of the A_0-mode, in order to achieve a good A_0-B_0 coupling later. The A_0-eigenfrequency must be determined (e.g. by blowing across the ff-holes) with the sound post inserted, as the sound post shifts A_0 to a significantly higher frequency.

Note: Depending on the individual graduation of neck and scroll the suggested frequency ratio (1.67-1.68) can vary as the B_0 eigenfrequency depends also on the stiffness of the neck and on the mass of neck, scroll and pegs. Each maker should establish their own frequency ratio by simple tests.

A certain amount of fine tuning of the fingerboard can be carried out after it is glued on, by shortening its length. An experiment involving successive shortening of a fingerboard in small increments, measuring B_0 and T_f eigenfrequencies and curve-fitting the resulted data cloud, resulted in the following empirical formulae for eigenfrequency shifts of B_0 and T_f modes:

(III): Increase of B_0 eigenfrequency (in %) =

$$\Delta L^*(0.1531^*\Delta L + 1.3097)$$

where ΔL = length reduction of the fingerboard (in %); length = 270 mm being 100% for the violin. The curve fit has high accuracy of R = 0.9979.

> *Example: Shorten the fingerboard from 270 mm to 265 mm, which is a reduction ΔL of 1.85%. Insert in formula III:*
>
> *Increase of B_0 eigenfrequency (in %)*
> *= 1,85*(0.1531*1,85 + 1.3097) = 2.95%*
>
> *So if B_0 used to be 250 Hz, by shortening the length of the fingerboard by 5 mm it will rise by 2.95% to 257.4Hz.*

(IV): Increase of T_f-eigenfrequency (in %) = 1.6246* = ΔL

Again the curve fit of this empirical function has high accuracy of R = 0.9972.

> *Example: Shorten fingerboard by 5 mm and insert this percentage of length reduction (ΔL = 1.85%)*
>
> *Insert in formula IV: Increase of T_f-eigenfrequency (in %) = 1.6246*1.85% = 3%*
>
> *So if T_f used to be 510 Hz, by shortening the length of the fingerboard by 5 mm it will rise by 3% to 525.3 Hz.*

These formulae provide a certain latitude for later adjustments of the fingerboard. Nevertheless it should be noted that the main frequency-sensitive working step when making the fingerboard comes from its thickness and the concave hollowed out area (particularly length and depth of that area) on the underside.

Of course, as well as fingerboard studies many other parameter studies focusing on other elements of the violin can be useful. Good examples of such "simulation experiments" are to be found in the work of Rodgers [15;16], using the Finite-Element Method for investigating the acoustics of the bassbar, thickness graduation etc.

C) Controlling the making process of new instruments

When acoustical tools are used in the making process of a violin, an obvious approach is to learn from the acoustical properties of existing fine instruments whose tonal quality is highly regarded. Modal analysis as a diagnosis tool and sound analysis as a controlling tool can be very valuable here. They can help to match the modes being modified by the various steps in the making process as closely as possible to those of the reference instrument [17, 18]. At the end of the making process psychoacoustical sound analysis can control (and potentially optimize) the final result. While one aim could be to make a "tonal copy" (more precisely a "resonance copy") of one particular reference instrument, another (perhaps more artistic) aim would be to understand the typical characteristics of various reference instruments from their modal behavior and tone and to create an individual "modal composition".

The term "tonal copy" must not be misunderstood as creating complete identity, but rather as guaranteeing a clear affinity of the two instruments. Confirmation of the success (through the similarity between original and "tonal copy") can only be given by the musicians who know and play both instruments.

Example: A television team of ‘Norddeutscher Rundfunk (NDR)’ recently filmed our studio and some details of our methods for a documentary program. They also filmed a young German soloist playing in the Münchner Max-Joseph-Saal on the Joseph Guarneri del Gesu 1733 mentioned earlier, and on a “tonal copy” of that instrument which had recently been made in our studio. Immediately afterwards they recorded the owner’s opinion, which was “Both instruments have the same qualities. But it is not just that. I have played quite a number of ‘Strads’ and ‘del Gesus’, but never have I had such a comparable feeling and tone as between my ‘del Gesu’ and that new violin.”

As shown in Fig. 2a the two resonance profiles are not identical. But it has been possible to recreate some typical tonal characteristics. These are especially:

- The quality (eigenfrequencies, ratios between levels) of corpus resonances. Modes below 500 Hz clearly show higher radiation than the higher-frequency B_1-mode which for both violins is around 540 Hz.
- Gaps between resonance regions.
- A general similarity of the “envelope shape” of the resonance profile.

Comparing the overall loudness of both instruments as a function of musical tones, Fig. 10b shows the slightly higher values of the “tonal copy”. This figure reveals the dynamical reserves of both instruments. The maximum differences of loudness between the musical tones are 10 phon for the original and (because of a slightly higher radiation of the T_1-mode) 12 phon for the copy.

Example: In order to judge the magnitude of differences between these two violins, Fig. 2b shows a comparison of the resonance profiles of the Stradivarius 1712 (“Schreiber”) and the Guarneri del Gesu 1733. A general difference in the frequency range of the corpus resonances is obvious. The frequency difference between T_1 and B_1 mode is smaller for the Stradivarius. Not only are these modes pulled further apart in the Guarneri, but the latter also shows a higher radiation of the lower frequency T_1 mode compared with the higher B_1 (for detailed explanations of these modes and description of their mode shapes, see Part I).

Example: Similarly revealing could be a comparison of the resonance profiles of two violins by Antonio Stradivari (1712 and 1727) as given in Fig. 2c. In the lower frequency range (particularly around the corpus resonances 400-600 Hz) there occur considerable differences which support the idea that even Stradivari did not copy himself (at least this is true for the present-day acoustics of those instruments, but it says nothing about how much they have been modified over the centuries). Nevertheless, clear similarities occur in the higher frequency region. This is also obvious from the loudness differences of musical tones in the higher ERB-regions (Fig. 6). It shows that the acoustical differences between the two violins by Stradivari are not inconsiderable compared with the differences between Stradivari (Fig. 2c) and tonal copy (Fig. 2d). As an indication of the “dynamical reserves”, the (comparable) overall loudness of both instruments is given in Fig. 10c. A comparison of the specific loudness differences between Stradivarius and tonal copy (Fig. 7) shows that the tonal copy accentuates the middle frequency groups (14-24 ERB) even more than the original Stradivarius – an accentuation which seemed to be typical for Stradivarius as compared with Guarneri (see above).

Example: Since the tonal copy of the Guarneri seemed to be a successful attempt to emulate typical Guarneri characteristics, it is not too surprising that a comparison of the specific loudness differences between the two tonal copies (Fig. 8) show the same “genus-differences” as those between the two original violins: compare Fig. 4 (original) with Fig. 8 (tonal copies). Musicians recognized each instrument immediately as being typical violins of the respective “genus”. A major factor in achieving successful results when making “tonal copies” is the parameter studies mentioned earlier. Empirical studies of the shift of eigenfrequencies and modifications of mode shapes show the advantage of modifying the corpus rather than the free plates [17, 18].

Example: Such parameter studies can broaden one’s experience about which modifications will be successful when aiming to implement a certain tonal task. As an example in the working process the thickness graduation is modified in various steps and the acoustical consequences documented. Fig. 14 shows the modifications of the back plate of a developing “tonal copy” (the

Figure 14. Thickness modifications in the working process. The grey values represent the amount of further thinning (max. 0.8mm) of the plates.

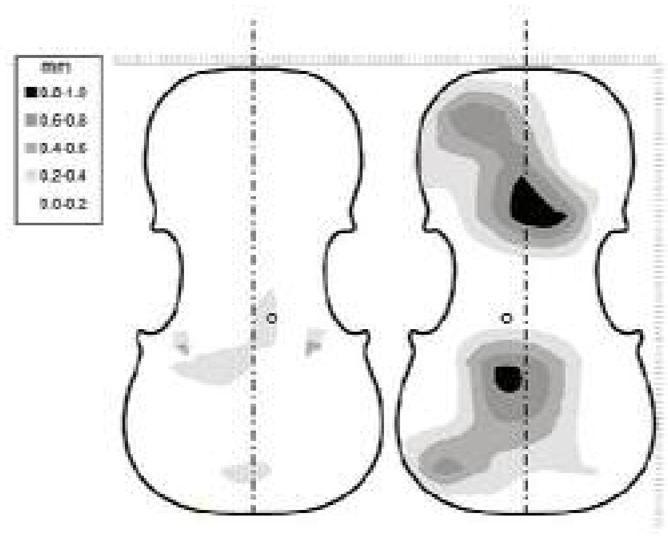
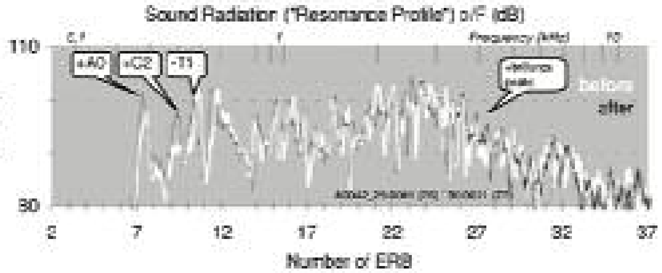


Figure 15. Effect of thickness modification (fig. 14) on the „Resonance Profile" and thus on the change of psychoacoustic perception (fig. 9). Corpus resonances have changed their ability to radiate sound. A_0 and C_2 increase their radiation level. Increase of levels and level-differences in the brilliance region and thus increase of brilliance and modulabilty (explanations see text „resonance damping and vibrato").



darker the area, the more wood was taken away, see scale). The psychoacoustical effects of the modified resonance profile are given in the loudness-difference diagram (Fig. 9). The effect is particularly noticeable in an increasing specific loudness in the lower critical bands up to 14 ERB and for the higher musical tones in an increase above 28 ERB. A comparison of the resonance profiles before and after the named modification is given in fig.15. It shows the changes of radiation levels and eigenfrequencies of single modes: Particulary the increased radiation of both the Helmholtzresonance A_0 (by 3.5dB) and the torsional corpus mode C_2 (by 6dB) is obvious. Furthermore the eigenfrequencies of the T_1- and B_1-corpus modes appear to be slightly shifted down. The radiation level of the T_1-corpus mode is reduced by 2 dB

Although such studies can undoubtedly be helpful, the use of the "empirical tools" described here (Fig. 16) will in our opinion never replace the "normal" working processes of the violin maker, which will still be characterized by many "trials and errors", nor will it replace the emotions during the working process of making an artistic object. An advantage of those acoustical tools might be that they allow one to gain more information from the inevitable "errors". Quite often a whole series of instruments that are intended to follow the resonance profile of one particular reference instrument will be constructed before one may reach a result that could justifiably be called a "tonal copy".

In my opinion the immediacy of such a success still has a lot to do with how emotionally one "understands" the reference. With Guarneri del Gesu it was the very first (out of a two-year series) that seemed to score a hit comparing it with the 1733-genuine 'del Gesu', while a troublesome series of several violins following the "Schreiber" Stradivarius model had to be made (trying numerous material and construction modifications) until a strong relationship

Figure 16. Measuring sound radiation on a turntable tripod by means of an impact-hammer-pendulum.

with this Stradivarius resulted. The projection of that tonal copy had to be demonstrated in the soloistic situation, when during the last concert period its owner, the leader of the Philharmonisches Orchester Ulm, played Béla Bartók's concerto No. 2 "against" the orchestra on that new violin. He states, "Although I have played a nice 18th century Italian fiddle for the last seven years, it is only since I began to play this "young Strad" that people have come to me after the concerts to ask about the instrument I was playing."

Obviously it is not important to play a violin made in the 18th century, but rather one which may be called a successful "resonance sculpture". What a blessing that we may benefit from some of the outstanding sculptures that already exist! Empirical acoustical methods can be tools for collecting evidence. The deciphering of fascinating acoustical 'secrets' of outstanding instruments can yield a vast store of experience. I believe we can carry on where they left off. That is why (after some preliminary exercises) currently we try to create violins that combine some beloved essential attributes of two of our reference violins: the soloistic power and passion of the 'del Gesu' (1733) and the unsurpassed richness of varying colors, depth and warmth of a Domenico Montagnana (1729).

CONCLUSION

One of the major messages of my work is that the terms "tone" and "acoustics" must not be confused. Acoustics is characterized using physical language ("mode shapes", "eigenfrequencies", "sound pressure", etc.), whereas tone is an aesthetic, rather than a physical, quantity. Aesthetics is not a discipline of physics but belongs to the field of art and philosophy. Although "tone" has its origin in acoustical processes, the sensation and quality of tone cannot be described using physical terms. Acoustics demands an intellectual attitude, while tone demands instead an existential realization. If tone is thought of allegorically as a painting, then acoustics is comparable with the colors of that painting. Of course the painting consists of a certain distribution of colors, just as tone consists of a certain distribution of sound pressure. But it would be absurd to claim that the aesthetic quality of the painting and its artistic content would be understood by a pure analysis of the frequency distribution and the spectrum of its colors. If the musician is a painter and the composition his motif, then the resonances of the instrument are the colors that he can use to express himself. The art of violin making is to provide an instrument whose palette of colors allows the musician to express what he feels and hears. The resonance profile of the instrument is nothing but this palette. I hope the examples in this paper have thrown some light on this palette.

Martin Schleske, München, den 27. Feb. 02

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