

# Resonance analysis and psychoacoustics in violin making

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## Summary

Resonance analysis is an acoustic measurement method developed in the Martin Schleske Master Studio for Violinmaking as a diagnostic tool for adjusting the sound of violins, violas, and cellos. Acoustic resonance analysis is used to represent the sound radiated by the instrument in a way that is audible to the human ear. It reveals the individual “resonance profile” of the instrument as well as the excitation patterns of the human inner ear.

For many decades, a small international community of acoustic researchers has been striving to uncover the tonal secrets of the violin through acoustic measurements. The analysis results are generally presented using standard physical functions (known as transfer functions). However, this does not go deep enough. Our work illustrates how physical measurements can complement and enrich artistic work in the workshop in a musically relevant way. Psychoacoustic evaluation of the ‘harmonic structure’ reveals the excitation patterns of the inner ear. This enables us to extract musically relevant information from the physical analysis. Differences in sound and quality between different instruments are made visible by acoustic ‘maps’.

The levels of sound radiation have their acoustic cause in the vibration modes of the resonances. While these vibration modes can be identified using experimental modal analysis (structure-borne sound analysis), the acoustic effect of the resonances is made visible using airborne sound resonance analysis. By analyzing both the acoustic *cause* and the acoustic *effect* of the instrument, modal analysis and resonance analysis form comprehensive diagnostic tools in acoustic violin research in our workshop.

## COMPARISON OF RESONANCE PROFILES

The transfer function commonly used in physics is represented by plotting the sound pressure  $p$  over the exciting force  $F$  as a function of frequency. This creates a “resonance profile” that reveals the character of the instrument through a multitude of individual resonance peaks. Fig. 1 shows the resonance profile of a violin by Antonio Stradivari from 1721 compared with a contemporary violin (Martin Schleske – Op. 371) from 2025. The latter was made from 50,000-year-old New Zealand kauri wood in our Master Workshop for Violinmaking.

Thanks to the exceptionally high acoustic quality of this tonewood, it was possible for us to craft a modern instrument (black curve) with a radiation that is

equal to that of Antonio Stradivari's violin (red curve) and superior in some areas.

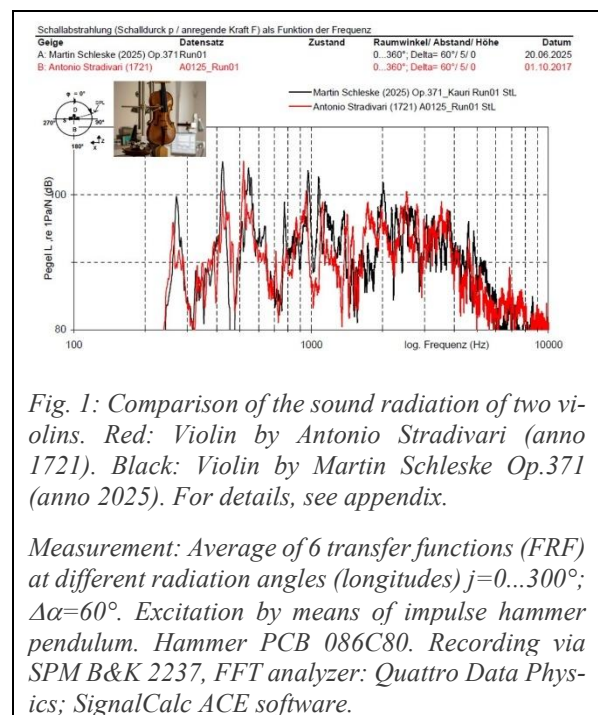
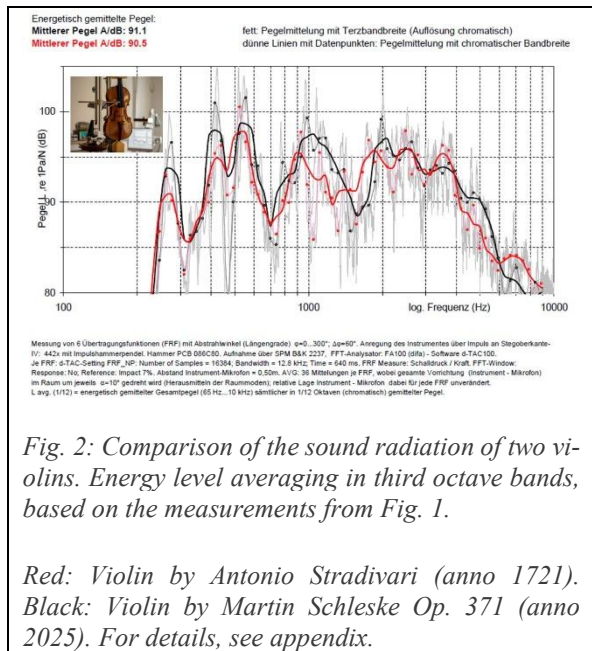


Fig. 1: Comparison of the sound radiation of two violins. Red: Violin by Antonio Stradivari (anno 1721). Black: Violin by Martin Schleske Op.371 (anno 2025). For details, see appendix.

Measurement: Average of 6 transfer functions (FRF) at different radiation angles (longitudes)  $j=0...300^\circ$ ;  $\Delta\alpha=60^\circ$ . Excitation by means of impulse hammer pendulum. Hammer PCB 086C80. Recording via SPM B&K 2237, FFT analyzer: Quattro Data Physics; SignalCalc ACE software.

High resonance is considered a necessary and desirable tonal characteristic for a solo instrument. At the same time, the newly crafted instrument is based on Stradivari's model in terms of design and tone color – see the section on “tonal copies”. For this reason, my workshop aimed to use the characteristic resonance areas of Stradivari's instruments as a model.

An energetic averaging of the transfer function over a certain frequency bandwidth illustrates the acoustic energy distribution of the resonance areas. Fig. 2 shows a corresponding level averaging over the individual resonances in third-octave bandwidths. The transfer functions from Fig. 1 are shown, but smoothed by this averaging. The soloistic power of the newly crafted instrument from 2025 is evident. This acoustic analysis is an invaluable control tool for the daily work of our violin workshop.



## EU CRAFT PROJECT

During a two-year research project funded by the European Commission (CRAFT Project 1999–2000), we had the opportunity to develop a method for analyzing the sound radiation of violins and representing it in a way that is audible to the human ear. The aim was to gain essential insights into the relationships between subjective perception variables (“sound”) and objective stimulus variables (“acoustics”). This required, on the one hand, the investigation of subjective assessment criteria suitable for characterizing the sound of a violin and, on the other hand, the investigation of measurable acoustic variables contained in the radiated sound. In the following, I will give a brief overview of some of the results.

## HEARING TESTS

During the course of the project, two violinists—Ingolf Turban and Michael Dinnebier—played the same pieces of music, motifs, and passages on eight different violins. Short sequences were selected from the three hours of audio material for a subsequent hearing test. The attributes examined were as follows:

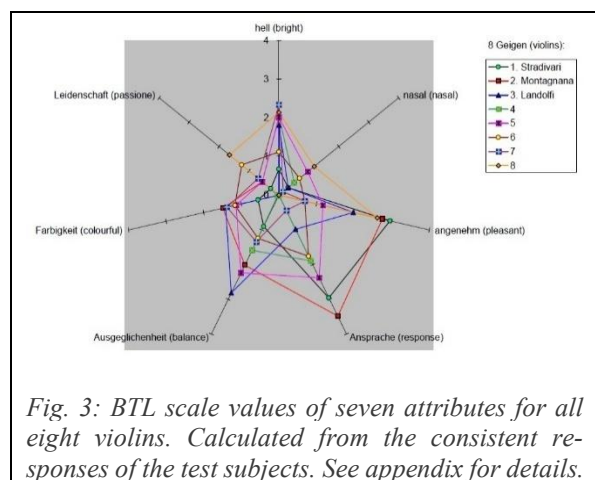
- light – dark
- nasal – not nasal
- balanced – unbalanced
- pleasant – unpleasant
- good response – poor response
- colorful – monotonous
- passionate – boring

The listening test was conducted using paired comparisons, whereby the test subjects had to assess which sound better corresponded to the attribute in question for all pairs by ticking a box.

The eight violins covered a range of different qualities: starting with Antonio Stradivari (1721), Domenico Montagnana (1729), Carlo Ferdinando Landolfi (1750) and ending with a simple Bohemian-Saxon student violin (around 1900).

The results showed a surprisingly high degree of consistency: the individually assigned rankings of the violins that were better or worse suited to the respective attribute were maintained very consistently for all eight violins. Circular triads indicate the degree of inconsistency. A combination of responses  $A > B > C > A$  (known as a circular triad) is considered inconsistent. On the other hand, it was found that although individual test subjects were able to deal consistently with the attributes queried, their individual definitions of the attributes differed. In other words, different people assessed the instruments consistently, i.e., they adhered consistently to their own individual ranking. However, the rankings determined by the individual test subjects differed significantly from one another in some cases (depending on the attribute). Further listening tests with a larger number of test subjects are to be carried out.

The ratings for the eight instruments are shown below:



The network diagram in Fig. 3 shows, for example, that Violin #1 (Antonio Stradivari 1721) is not considered to have a particularly bright sound (0.67), but is nevertheless perceived as pleasant (2.96). Furthermore, this violin is perceived as having good response (2.96). Violin #7, on the other hand, is rated as very bright sounding (2.34) but not very pleasant (0.69) and with poor response (0.44). It is also apparent that there were no significant differences in the rating of the attribute “nasal.”

## METHOD

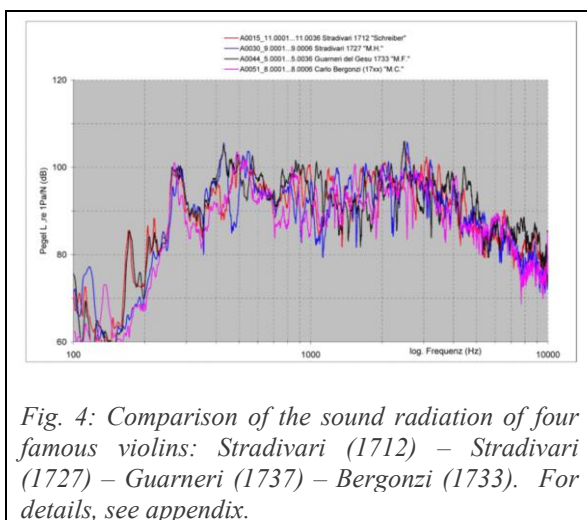
The method developed at Martin Schleske's master violin-making workshop for determining the sound radiation of violins is based on the following steps:

- Spatial measurement of radiated sound
- Energetic averaging: Resonance profile of the instrument
- Determination of the harmonic levels of all playable tones
- Representation of the excitation patterns of the basilar membrane in the human inner ear and by this determination specific loudness.

The measurement of the radiated sound is based on a two-channel Fourier transform. The ratio of radiated sound pressure ( $p$ ) to exciting force ( $F$ ) is determined. The analyzed variables are displayed in absolute terms. Both variables ( $p$  and  $F$ ) are frequency-dependent. In physics, this frequency dependence is usually represented as a function (diagram curve). The curve shows the transmission factor of  $p/F$  (strength of sound radiation) for each frequency represented. This curve is therefore called a frequency response function (FRF).

Fig. 4 shows a comparison of four FRF's of famous violins from the old Italian violin-making tradition:

- Antonio Stradivari (anno 1712)
- Antonio Stradivari (anno 1727)
- Joseph Guarneri del Gesù (anno 1737)
- Carlo Bergonzi (anno 1733)



Both the construction and acoustics of the four violins shown were analyzed in detail at Martin Schleske's master violin-making workshop. It was found that the body resonances of the Stradivarius from 1712 (red) are more similar to those of the Bergonzi (purple) than to those of the second Stradivarius from 1727 (blue). Similarly, the resonance profile

shows stronger similarities between the late Stradivarius from 1727 and the Guarneri del Gesù from 1737 (black) than between the two Stradivarius violins.

The physical variables required for the transfer function FRF – exciting force  $F$  and radiated sound pressure  $p$  – are measured using the excitation microphone shown in Fig. 5: The measuring microphone connected to the sound pressure level meter is mounted on a tripod arm so that it can be rotated around the instrument, which is secured to the neck by a foam ring. The force is applied to the instrument via a miniature impulse hammer commonly used in modal analysis at the upper edge of the bridge in the direction of the bow stroke.



Fig. 5: Excitation mimicry: tripod with ball-bearing impulse hammer pedal.

The transfer function FRF measured in this way and calculated using Fourier transformation would not yet provide a comprehensive representation of the instrument's sound radiation. The reason for this is the instrument's directional radiation characteristics: a violin does not radiate its vibration modes evenly in all directions. The curve of the transfer function FRF therefore depends heavily on the direction in space. In order to obtain a representative result for the sound actually radiated by the instrument, a large number of transfer functions FRF must therefore be determined in different spatial directions. These transfer functions FRF are then sensibly represented not as individual curves, but as a colored "map."

The following illustrations show such sound radiation maps. The color value represents the strength of the p/F level (dB) (red = strong level, blue = weak level). The x-axis again represents the frequency. However, the y-axis now shows the radiation angle (circle around the instrument with axis of rotation parallel to the violin neck; height of the circle at scale length) around the instrument: angles of 0° and 360° correspond to the normal vector of the top plate, 180° to the normal vector of the back plate.

If you follow the color gradient horizontally on this contour diagram, the color change indicates the frequency dependence of the sound radiation in a single radiation angle. Vertically, the color bands show the directional dependence at a single frequency.

If a vertical color band remains largely unchanged in color, this means that sound radiation is direction-independent at this frequency. In physics, this is referred to as a vibration mode with monopole character. This is generally only the case in the low-frequency range of the violin. On the other hand, it is clearly recognizable that in the high-frequency range, an increasing fragmentation of the sound radiation begins: here, the resonances “fire” the sound more strongly in some directions of the room than in others. This is the main reason for the “liveliness” and “spatiality” of the sound. The fragmentation in this frequency range, which manifests itself in numerous small islands of color, illustrates how much the instrument allows the musician to ‘play’ with this spatial direction-dependent firing of the resonances through changes in vibrato and bowing.

The sound radiation maps make it possible to illustrate the tonal differences between different instruments. In addition, different states of one and the same instrument can be compared with each other (for example, in the case of restoration or sound adjustment). This allows conclusions to be drawn about the tonal effect of changes made (finishing, sound post displacement, bridge changes, etc.).

The following Fig. 6 shows that numerous characteristic features can be derived from such a “sound radiation map”. The instrument shown is an analysis of a cello by Domenico Montagnana from 1740. Below the colored contour diagram is the resonance profile of the sound radiation, as determined from the energetic average of all solid angles. The heights of the individual resonance peaks in the resonance profile are thus a measure of the strength of the sound radiation. The color strip vertically associated with each resonance peak is in turn a measure of the spatial directional characteristic of the respective resonance. Both the strength of the sound radiation and the directional characteristics result from the corresponding vibration mode of each resonance. The interplay of many different modes determines the acoustic character of the instrument. (For information on the

significance and measurement method of vibration modes, see the section on modal analysis on this website.)

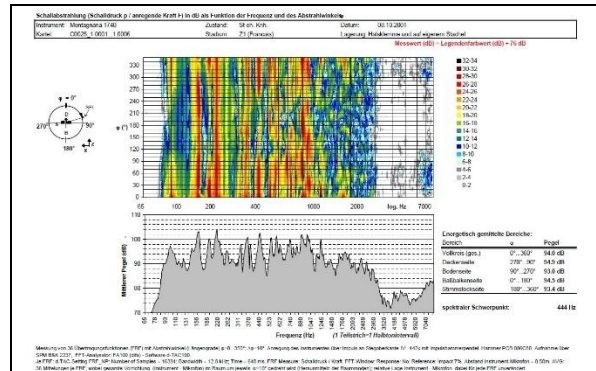


Fig. 6: “Sound radiation maps” of a cello by Domenico Montagnana (anno 1740).

If you follow the color gradient horizontally on this contour diagram, you can see the frequency dependence of the sound radiation (at a single radiation angle) from the color change. Vertically, the color changes reveal the directional dependence (at a single frequency).

See appendix for details.

The acoustic analysis of the shown Montagnana cello reveals the following characteristic features:

**Helmholtz resonance:** The level of this lowest main resonance of the cello (just under 100 Hz) is perpendicular (0°) to the top plate (max. level) and just under 10 dB above the minimum level perpendicular (180°) to the backplate.

The radiation of a main body resonance at 217 Hz is relatively direction-independent, while a body resonance at 194 Hz exhibits strong directional dependence. Here, the maximum of 105 dB is in the range of directional angles 0...90°, i.e., in the direction of the ceiling on the bass bar half, while the minimum of 77 dB is at a directional angle of 150° in the direction of the floor (also on the bass bar side).

In the octave range between 200 and 400 Hz, the cello exhibits numerous effective and largely direction-independent resonances, recognizable by strong, i.e., red-orange-colored and consistent vertical stripes. In the resonance range 400–1000 Hz, there is an increasing formation of directional lobes with direction-dependent level differences of sometimes more than 20 dB.

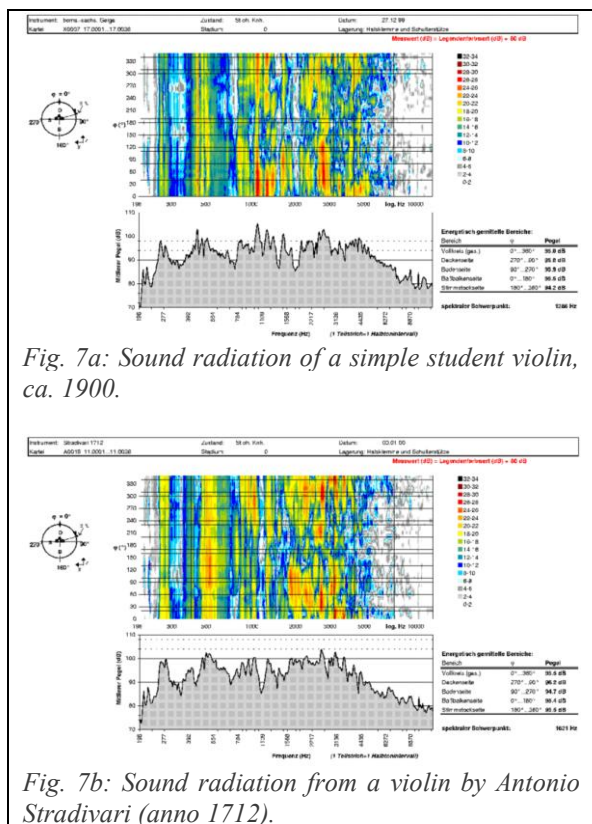
The resonance range between 1000–3000 Hz is characterized by countless smaller level islands. Due to the steepness of the resonance peaks, i.e., low resonance damping, the levels of the overtones that fall

within this resonance range react strongly to the musician's vibrato. This results in great liveliness and musical malleability of the notes played.

Above 3 kHz, a strong low-pass filter effect sets in. This steep level drop in the range around 3 kHz is desirable in terms of sound, as it enables a “velvety” – or, as some musicians say, “Italian-sandy” – tone that is by no means too sharp. In terms of energy, the total radiation (averaged over all frequencies) towards the ceiling (direction angle 270...90°) is just under 2dB above the radiation towards the floor (direction angle 90...270°).

For violin making practice, it is instructive to compare instruments of different perceived sound quality acoustically. Fig. 7 shows a simple student violin (circa 1900) compared to the famous “Schreiber” Stradivarius (circa 1712). The comparatively significantly higher sound level components of the Stradivarius in the low-frequency range (200–600 Hz) and the higher sound components of the student violin in the nasal range (1000–1600 Hz) are immediately apparent.

The spatial sound radiation can also be displayed individually for any frequency. The form of the network diagram is conveniently chosen for this purpose.



The information contained in the corresponding colored sound radiation map is shown in Figs. 8 and 9

in the form of directional diagrams (level as a function of the directional angle) for numerous resonance peaks. Here, too, the characteristics mentioned—such as directional maxima and directional lobes—are clearly visible.

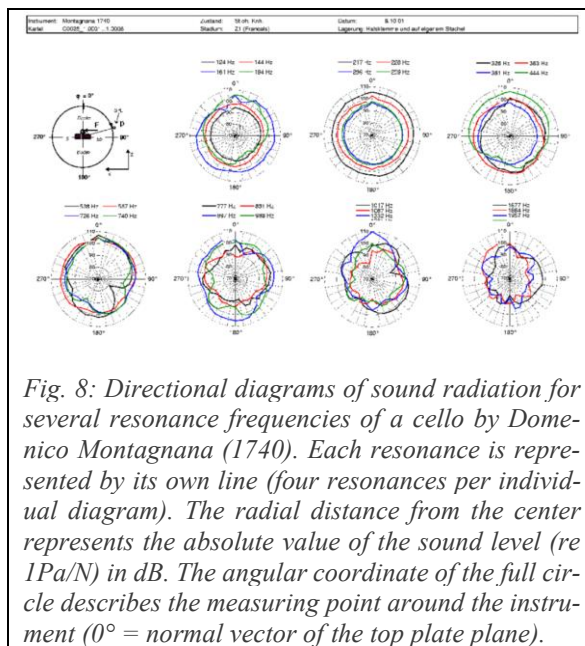


Fig. 8: Directional diagrams of sound radiation for several resonance frequencies of a cello by Domenico Montagnana (1740). Each resonance is represented by its own line (four resonances per individual diagram). The radial distance from the center represents the absolute value of the sound level (re 1 Pa/N) in dB. The angular coordinate of the full circle describes the measuring point around the instrument (0° = normal vector of the top plate plane).

The rather spherical sound radiation at low frequencies and the strongly fragmented radiation at higher frequencies are clearly visible.

The following illustration shows the acoustic map of a violin by Joseph Guarneri del Gesù (anno 1733), also represented as a corresponding network diagram:

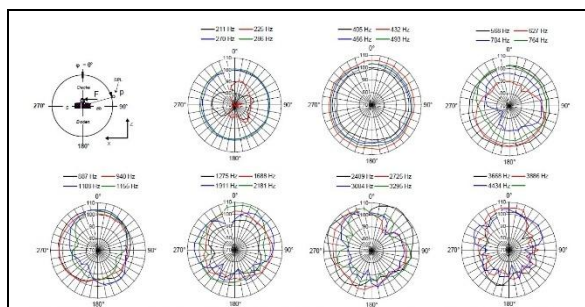


Fig. 9: Sound radiation from a violin by Joseph Guarneri del Gesù (1733):

Level based on the ratio of sound pressure  $p$  to exciting force  $F$  as a function of the radiation angle (directional characteristic) around the instrument.

The directional characteristics for 20 individual frequencies are shown. The frequencies of the vibration modes in the range 211–3295 Hz were selected.

It is immediately apparent that the low-frequency modes are characterized by spherical radiation characteristics, while the higher-frequency modes above approximately 1000 Hz increasingly exhibit more or less pronounced directional beams. This strong fragmentation is of essential importance for the musical liveliness of the tone.

## HARMONIC STRUCTURE

An analysis of sound radiation is all the more meaningful when the chosen form of representation of the resonance profile corresponds to the actual musical situation. For this reason, a program was developed at Martin Schleske's master violin-making workshop that can be used to display the resonance profile of sound radiation in a musically relevant way – the “harmonic structure”:

The “harmonic structure” is a three-dimensional representation of the radiated sound. The levels p/F are plotted as a function of the frequencies of the musical tones and their associated first 15 harmonics.

It can be seen that this representation makes the musical differences between different violins more recognizable than the two-dimensional transfer function FRF line diagram commonly used in physics.

The following Fig. 10 shows the ‘harmonic structure’ of a violin by Joseph Guarneri del Gesù (anno 1733).

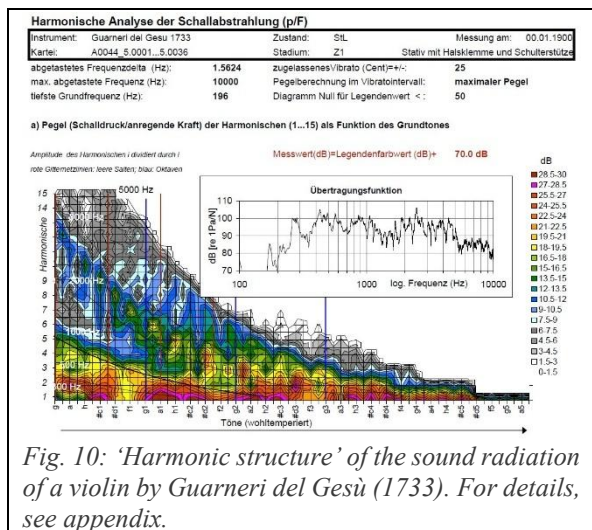


Fig. 10: ‘Harmonic structure’ of the sound radiation of a violin by Guarneri del Gesù (1733). For details, see appendix.

The ‘harmonic structure’ reveals the musical relevance of the physical transfer function FRF: for example, the resonance peak at the frequency of the fundamental tone a1 (440 Hz) reappears simultaneously as a resonance peak at the second harmonic of the fundamental tone a (220 Hz) (follow the curved line!). This is because both the second harmonic of

the fundamental tone a at 220 Hz and the fundamental tone a1 at 440 Hz fall on the resonance peak of the T1 body resonance of the instrument.

The same applies to the resonance peaks around 2000–2300 Hz. These two resonances contribute to sound radiation in the range of the high fundamental tones h3 to #d4, and are also responsible for the strong sound level components of the second harmonics of the musical tones one octave lower, and in turn for the sound components of the third harmonics of the musical tones another fifth lower; etc. The fundamental importance of the high-frequency resonances of the instrument – on the one hand for the fundamental tones of the high musical tones, and on the other hand for the higher harmonics of the low musical tones – thus becomes clearly apparent. When playing a chromatic scale, the representation of the ‘harmonic structure’ corresponds clearly to the auditory impression. For example, the Helmholtz range of the G string around c1 is perceived as significantly more sonorous than the open G string. The weakly resonant range around f1 is also clearly audible and is represented in the figure by the green dip (according to the legend).

An alternative representation consists of displaying each individual harmonic as a function of the musical tone by means of cross-sections through the ‘harmonic structure’. According to the force spectrum generated by the musician's bow stroke, the amplitude of the i-th harmonic is divided by i. Fig. 11 shows such a ‘harmonic cross-section’ of the sound radiation for the first ten harmonics using the example of a violin by Antonio Stradivari (anno 1712):

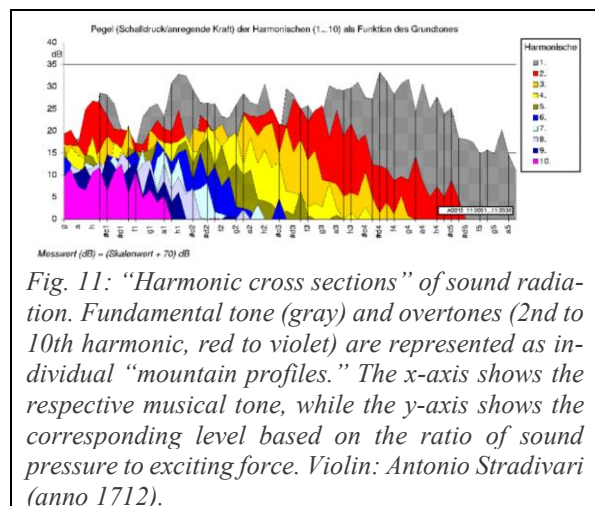


Fig. 11: “Harmonic cross sections” of sound radiation. Fundamental tone (gray) and overtones (2nd to 10th harmonic, red to violet) are represented as individual “mountain profiles.” The x-axis shows the respective musical tone, while the y-axis shows the corresponding level based on the ratio of sound pressure to exciting force. Violin: Antonio Stradivari (anno 1712).

Of particular interest are the “harmonic cross-sections” of sound radiation, especially due to the striking similarities between instruments that are subjectively classified as sounding good and those that sound less appealing or ugly.

For example, the violins by Antonio Stradivari that we examined show a uniformly decreasing, soft “hedgehog pattern” in the “harmonic structure,” whereas such a consistent pattern is not recognizable in more average student instruments. Furthermore, the levels of harmonics in Stradivarius instruments appear almost everywhere in a clear, decreasing order, while in average instruments, harmonics with a high order number often exceed those with a lower order number in their levels. Note in particular the range of the D string with the strong dip in the 1st and 2nd harmonics and a one-sided, dominant peak in the 3rd harmonic. The absence of the lower harmonics results in a “thin,” “rough,” “insubstantial” sound. The tone lacks volume and warmth.

My experience shows that frequent listening to instruments whose sound radiation is simultaneously present in the “harmonic structure” leads to an intuitive understanding of these colored maps. In this way, it is possible to learn to hear the harmonic structure of the instrument. This is particularly the case when listening to AB comparison recordings of two different violins and comparing both colored maps of the sound radiation with each other.

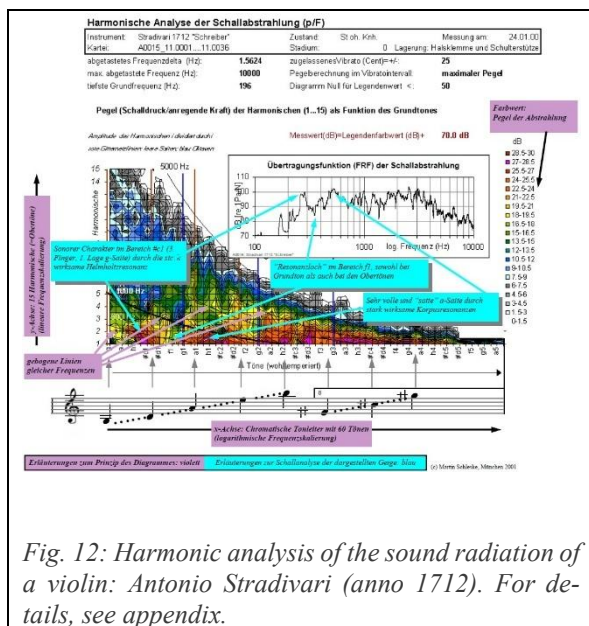


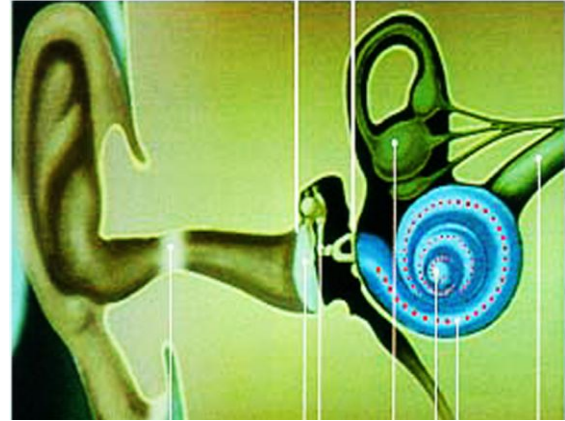
*Fig. 12: Harmonic analysis of the sound radiation of a violin: Antonio Stradivari (anno 1712). For details, see appendix.*

## PSYCHOACOUSTICS

A psychoacoustically relevant sound analysis of string instruments aims to represent the measured sound radiation of the instrument in such a way that the excitation pattern of the inner ear becomes recognizable.

The radiated sound is thus not only represented by physical stimulus variables, but in a further step also by psychoacoustic perception variables.

To this end, the master violin maker Martin Schleske developed analysis software that calculates and displays the specific loudness pattern for all playable notes from the measured sound. Not only the specific filter characteristics of the human ear are taken into account, but also all masking effects of the ear.



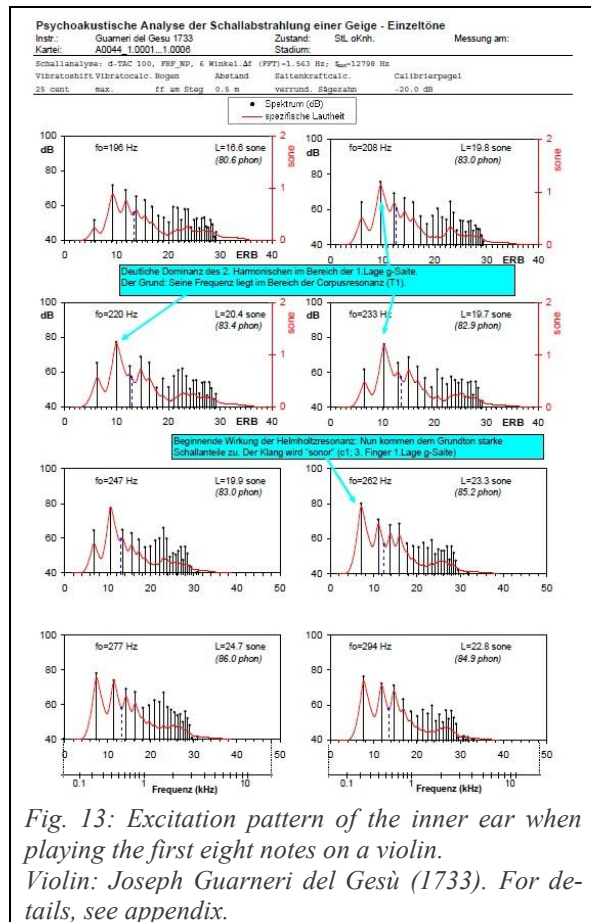
Psychoacoustic sound analysis has the following significance for violin making:

- Characterization of the instrument in terms of strengths and weaknesses
- Diagnostic tool for sound adjustment (sound post adjustment, fingerboard tuning, bridge, etc.)
- Acoustic comparison of two different instruments
- Enhanced understanding of differences in timbre

The first step is to measure the spatial sound radiation of the instrument. The measurement is performed using impulse excitation. The transfer function FRF is determined using Fourier transformation. This reveals the resonance profile of the violin.

This measurement gains musical relevance when the harmonic spectrum of all playable notes is subsequently calculated and displayed in the form of a colored contour diagram. Here, the resonances of the violin are plotted as colored layers of height (like the contour lines of a mountain range): peaks and troughs indicate strong or weak partial tones of the notes played. Attributes such as “bright” or “dark” sounding, ‘balanced’ or “unbalanced,” etc. thus become objectively visible.

Fig. 13 shows the psychoacoustic excitation patterns of the inner ear using the example of various individual tones, which were calculated from the transfer function FRF of the sound radiation and then evaluated psychoacoustically. Instrument: Violin by Joseph Guarneri del Gesù (anno 1733). This is the specific loudness representation of the first eight chromatic single tones of the G string.



The black dots with the vertical lines represent the discrete levels (dB) above the frequency (ERB) at which sound components were calculated from the measured transfer function FRF for the respective musical tone represented. This is done at the so-called harmonic levels, consisting of the level components of the fundamental tone and associated overtones.

The specific loudness calculated from the discrete sound components illustrates where and with what intensity the fine hair cells on the basilar membrane of the human inner ear are stimulated. The stimulation of the basilar membrane determines the neural activity that correlates with our perception of sound. By comparing the “physical information” (black dots) with the “psychoacoustic processing” (red curve), it can be seen that the hair cells of the inner ear are stimulated not only at the “physically present” discrete individual frequencies, but also – in the form of the curve of specific loudness – in a broadband “soft” range.

The blue dot with the dotted line in Fig. 13 marks the “spectral center of gravity” of the specific loudness for each musical tone. The spectral center of gravity is defined by the fact that the loudness components to the left and right of it are equal in size. Its position on the frequency axis (ERB) is thus a measure of the

timbre balance of the musical tone represented. (left = darker sound, right = brighter sound).

If we evaluate the red curve of the specific loudness, we can see the essential characteristics of the musical tones of the instrument. For example, there is a clear dominance of the 2nd harmonic (= first overtone above the fundamental tone) in the range from the 1st position to h1. The reason: the frequency of the second harmonic lies in the range of the body resonances. With C1 (third finger, first position, G string), the timbre begins to change significantly. The effect of the strongly “breathing” Helmholtz resonance sets in. Now strong sound components are added to the fundamental tone. The sound becomes ‘sonorous’ and “full.”

Using our program for psychoacoustic evaluation of the sound radiation of string instruments, we finally represent the specific loudness of all individual tones in the form of a contour plot. The color values represent the specific loudness as a function of the frequency groups (ERB). (The frequency axis derived from psychoacoustics with the unit ERB is known to correspond much better to human hearing than the frequency axis with the technically standard unit Hertz (Hz) – see in particular the work of Professor Brian C. J. Moore, Department of Psychology, University of Cambridge, UK). In the psychoacoustic “sound maps” like fig. 14 that we developed and use in our daily work in violin making, the basilar membrane is plotted on the horizontal axis, and a chromatic scale over 60 semitones is plotted on the vertical axis. To the left of the colored contour diagram, the overall loudness of these 60 chromatic tones is shown. It results from adding up the specific loudness values across all frequency groups.

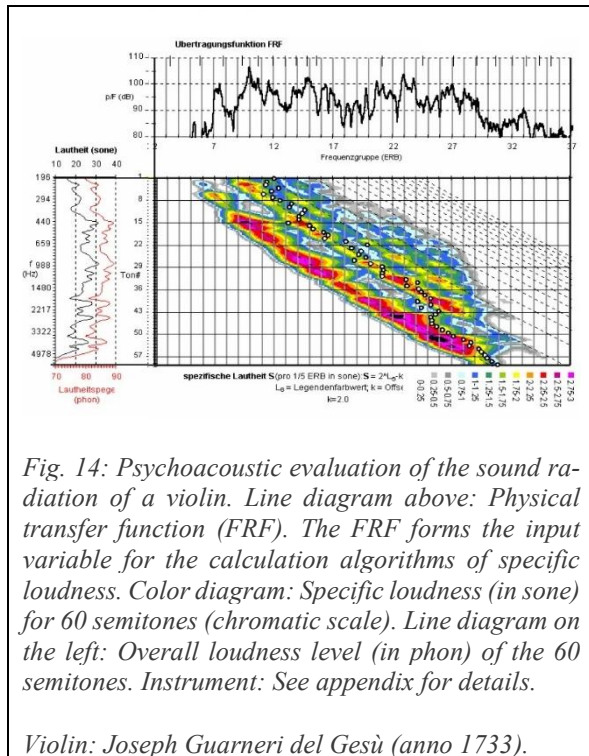
Such a psychoacoustic evaluation of the sound radiation of a large number of different violins reveals remarkable results. It is particularly obvious that the differences in sound between different violins are hardly noticeable when the absolute representation is chosen. Only a representation of the loudness differences between two violins makes the differences in sound clearly visible.

The complete representation of the loudness of all musical tones of an instrument is given in Fig. 14 below. This is the aforementioned violin by Joseph Guarneri del Gesù (anno 1733).

*Explanations for Fig. 14.*

The horizontal axis of the line graph (above) shows the frequency axis in ERB (frequency group 2...37), which corresponds to the local excitation on the basilar membrane of the human inner ear. The vertical axis shows the ratio of sound pressure  $p$  to excitation force  $F$ . The individual resonances are visible as resonance peaks. The color scale  $L_s$  represents the value

of the specific loudness  $S$  (in sone) in such a way that an increase by the value 1 corresponds to a doubling of the loudness impression:  $S=2^{\wedge}Ls-k$ ; with  $k$ =diagram offset (high loudness red, low loudness gray).



The horizontal axis (identical to the horizontal axis of the transfer function FRF) also represents the ERB frequency axis with the frequency groups 2...37 (gray vertical grid lines); the vertical axis represents the 60 musical semitones of the chromatic scale (tone#); black horizontal grid lines are arranged at intervals of a fifth: tone#1 = open G string; tone#8 = open D string; etc. Dashed diagonal grid lines = position of the harmonics.

The first (slightly curved) line on the left thus shows all first harmonics (fundamental tones); the second line shows all second harmonics, etc. The white dots in the color diagram indicate the position of the respective spectral center of gravity of the musical tones. The position in the horizontal direction is an indicator of the timbre of the corresponding musical tone (see above).

Line diagram on the left: Total loudness level (in phon) for the 60 musical semitones. The total loudness results from the addition of all partial loudnesses of the individual frequency groups (horizontal addition of the color values). This allows the “loudness balance” and the absolute loudness of an instrument to be represented across its entire playing range.

## ANALYSIS OF THE VIOLONCELLO

When comparing the various instruments in the string family, a fundamental acoustic weakness of the cello becomes apparent. Compared to the violin, the cello exhibits a fundamental weakness in performance on its two lower strings. Due to the natural “hard of hearing” nature of humans towards low frequencies and the fundamentally lacking resonance strength of the cello in this low frequency range, the inner ear is much less stimulated by the lower fundamental tones than by the higher fundamental tones.

These effects are all included in the psychoacoustic evaluation of sound radiation described above. One could say that the sonic “fireworks” begin higher up on the cello. This reveals a fundamental problem with the cello, which is easily audible to concertgoers, for example when a cello concerto is performed “against” an entire orchestra. Even with top-quality instruments (such as the famous “Isserlis” Montagnana shown here), the sound radiation achievable in this low-frequency range of the two lower strings is still too low.



Fig. 16 shows the psychoacoustic analysis of the cello mentioned above.

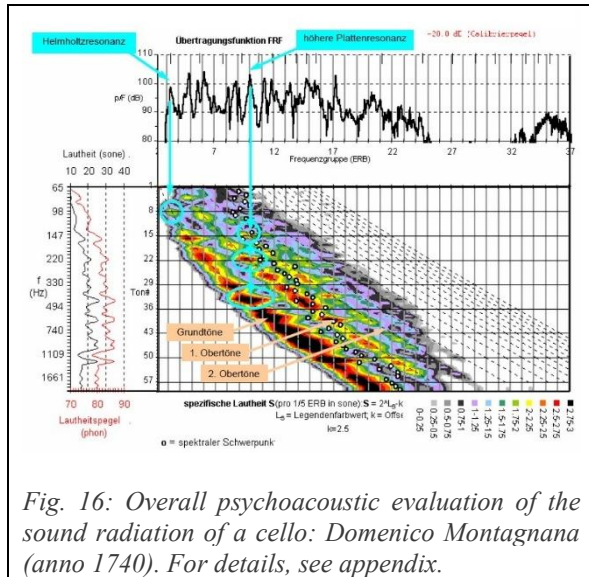


Fig. 16: Overall psychoacoustic evaluation of the sound radiation of a cello: Domenico Montagnana (anno 1740). For details, see appendix.

### Explanations for Fig. 16:

The loudness level  $L_s$  is shown as the color value. The relationship between loudness level  $L_s$ , loudness  $S$ , and offset  $k$  is given by:  $S = 2^{L_s - k}$ . Thus, the distance between two colors in the diagram always corresponds to the same subjective loudness difference, and a color value distance of  $\Delta L_s = 1$  corresponds to a doubling or halving of the perceived loudness. These calculations take into account the specific perceptual characteristics of human hearing—frequency dependence of loudness perception and spectral masking.

Regarding the violoncello shown: The low-frequency Helmholtz resonance (first resonance peak of the transfer function FRF at 3.4 ERB, or 100 Hz) only produces excitation when playing the 8th semitone (open G string); see light blue arrow and circle. In contrast, the effect of higher-frequency resonances is more diverse: for example, the distinctive plate resonance in the range of 10 ERB (or 444 Hz) is responsible both for the strong loudness in the fundamental range of 31...35 tone# and in the range of the open A string (22nd tone#) and for the strongly present first overtone. The same applies to the second overtone in the range of the G string (15th tone#); see the three light blue circles indicating loudness areas.

The resonance strength of the cello in higher frequency groups benefits a variety of musical tones (notes), namely the fundamental tone range of high notes as well as the overtone range of low notes. The same can be observed for all resonances of the instrument if one moves vertically downwards from the resonance peak of the transfer function FRF into the colored loudness diagram and pays attention to which of the 60 semitones – whether in the fundamental range, i.e. on the first diagonally dashed grid line on the left (see label “Fundamental”) or in the

overtone range, i.e. on the diagonally curved grid lines further to the right.

The following Fig. 17 shows the corresponding psychoacoustic analysis of a cello by Francesco Gofriller.

In principle, the aforementioned weakness of the cello as an instrument type is also impressively demonstrated here: there is a fundamental problem in that the low-frequency range of the basilar membrane is not sufficiently excited. This is due, on the one hand, to the lack of effective resonances in this frequency range and, on the other hand, to the natural “hard of hearing” nature of humans towards low frequencies.

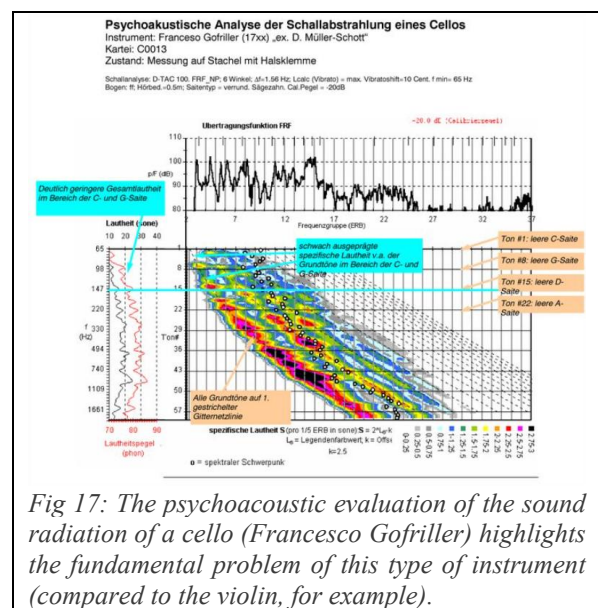


Fig 17: The psychoacoustic evaluation of the sound radiation of a cello (Francesco Gofriller) highlights the fundamental problem of this type of instrument (compared to the violin, for example).

As can be seen from the color gradient of the specific loudness in this diagram, the first two fifths (notes #1...#15) have a low loudness. This playing range therefore has little fundamental tone, which can be seen from the drop in loudness on the first (dashed) grid line of the first harmonic. The overall loudness (see curve diagram on the left) is also about 10 phon below the overall loudness occurring from the D string onwards.

The interface of the psychoacoustic analyzer for measuring and audibly representing the sound radiation of violins is shown in the following figures. In the sound practice of our studio, this “special tool” has proven to be extremely useful for evaluating parameter studies in the development of violins, violas, and cellos.

It has been used to conduct numerous studies of the various design parameters that significantly determine or alter the sound of the violin. These parameters were:

- Different bridges
- Different strings
- Different soundpost positions
- Different woods
- Different fingerboard finishes
- Model differences
- Variations in plate finish

The method of sound analysis is a useful tool for checking a newly made instrument and for optimization, both in terms of sound adjustment of valuable instruments and in the production of sound copies based on specified reference instruments.

## PSYCHOACOUSTIC PARAMETER STUDIES IN VIOLIN MAKING

Examples of psychoacoustic sound analysis of string instruments:

- Violin by Antonio Stradivari (1712) compared with Joseph Guarneri del Gesù (1733).
- Cello by David Tecchler (1719) compared with Stradivari-Lott.
- Cello by Francesco Gofriller compared with Domenico Montagnana (1740).
- Viola by Sannino (1906).
- Influence of sound optimization of a violin through sound post and bridge.
- Comprehensive sound adjustment of a cello (Stradivari-Lott) through new bass bar, sound post, and bridge.

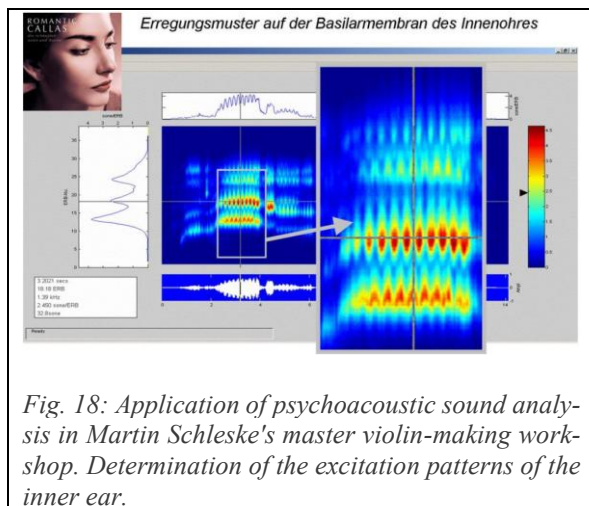


Fig. 18: Application of psychoacoustic sound analysis in Martin Schleske's master violin-making workshop. Determination of the excitation patterns of the inner ear.

The following examples show that string instruments are not simply classified as “good” or “bad,” but rather according to the specific character of the instrument.

**Example 1:** Fig. 19 shows the difference in specific loudness between two violins. Shown are a violin by Antonio Stradivari (anno 1712) and a violin by Joseph Guarneri del Gesù (anno 1733).

Both violins are considered first-class representatives of the old Italian school. It is clear that the Stradivari stimulates the middle range of the basilar membrane much more strongly, while the Guarneri causes stronger stimulation of the human inner ear in both the low-frequency and high-frequency ranges. We can certainly speak of typological differences here.

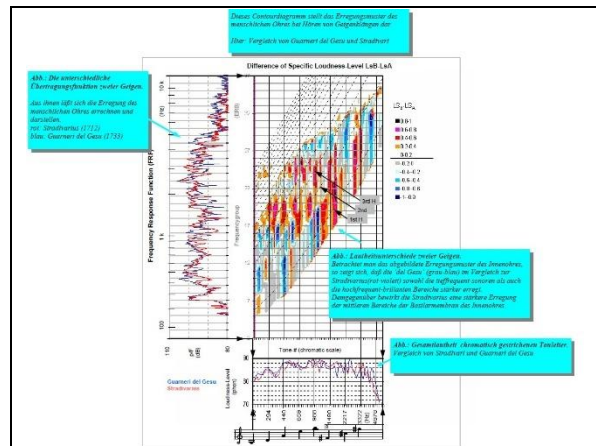


Fig. 19: Typical psychoacoustic differences between Stradivari (red coloring) and Guarneri del Gesù (blue coloring). The difference in the excitation patterns of the inner ear is represented by colored scales. It can be seen that Stradivari excites the frequency groups in the middle range of the inner ear more strongly, whereas Guarneri excites both the low-frequency and high-frequency ranges of the ear more strongly. For details, see the appendix.

**Example 2:** Fig. 20 shows a comparative sound analysis of a cello by David Tecchler (Rome 1719) from the Bavarian State Orchestra with a cello by Stradivari-Lott Cellos (top by Antonio Stradivari, back and sides by J.F. Lott).

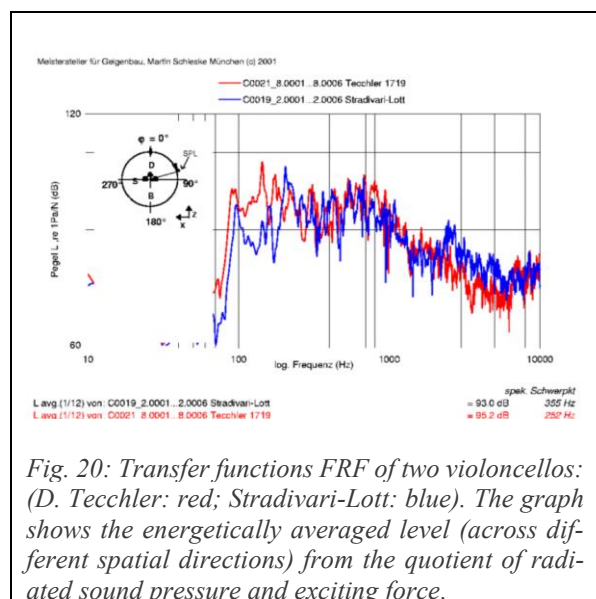


Fig. 20: Transfer functions FRF of two violoncellos: (D. Tecchler: red; Stradivari-Lott: blue). The graph shows the energetically averaged level (across different spatial directions) from the quotient of radiated sound pressure and exciting force.

The figure shows the resonance profiles of the sound radiation of both cellos, averaged over different spatial directions. It can be seen that the Tecchler cello has two strong body resonances in the low-frequency range at 156 Hz and 173 Hz. The comparable body resonances of the Stradivari cello are at significantly higher frequencies, at 204 and 223 Hz. These acoustic differences are also reflected in the auditory impression of both instruments: the Tecchler cello is considered one of the most outstanding cellos in the Bavarian State Orchestra due to its “bass strength.” The high levels in the fundamental frequency range of 100–200 Hz are remarkable, as they are significantly higher than those of the Stradivari cello.

The latter is – due to its different construction – a much more ‘tenor-like’ instrument with a stronger emphasis on the midrange. This can also be seen quantitatively in the resonance profile: in the frequency range between 2–3 kHz, which is decisive for the brilliance of the tone, the Stradivari cello has higher resonance levels (by up to 10 dB) than the Tecchler cello. The differences in timbre can also be seen by calculating the so-called spectral center of gravity: this is 252 Hz for the Tecchler and 355 Hz for the Stradivari-Lott.

Above and below the frequency of the spectral center of gravity, the energetically added level components of the resonance profile are equal. The higher the spectral center of gravity, the stronger the high-frequency components radiated. A high spectral center of gravity thus indicates a rather bright sound, while a low spectral center of gravity indicates a dark sound. The spectral center of gravity is given in Hz.

The energetically averaged level of the entire resonance profile is 95.2 dB for Tecchler, which is a good 2.0 dB higher than that of the Stradivari-Lott cello at 93.0 dB.

The difference in construction is already apparent in the differences between the models: the Tecchler cello (chest width in the C-bow 240 mm) is significantly wider in outline than the Stradivari cello (211 mm).

In the frequency range of the so-called a-formant (600–900 Hz), which is responsible for an “open tone,” the sound radiation of the Stradivari resonances is in some cases up to 6 dB (four times the sound power) higher than that of the Tecchler cello. This strong “resonance potential” causes a specific loudness that is almost twice as strong in the corresponding frequency groups of the inner ear. Conversely, the specific loudness of the Tecchler cello in the low-frequency fundamental range of the C, G, and D strings is almost twice as high as that of the Stradivari cello.

Incidentally, the fact that Stradivari's instruments emphasize the spectral midrange more strongly was also noticeable when comparing his violins with those of Joseph Guarneri del Gesù, for example. It seems to be a typological characteristic of Stradivari that his instruments emphasize the midrange very strongly.

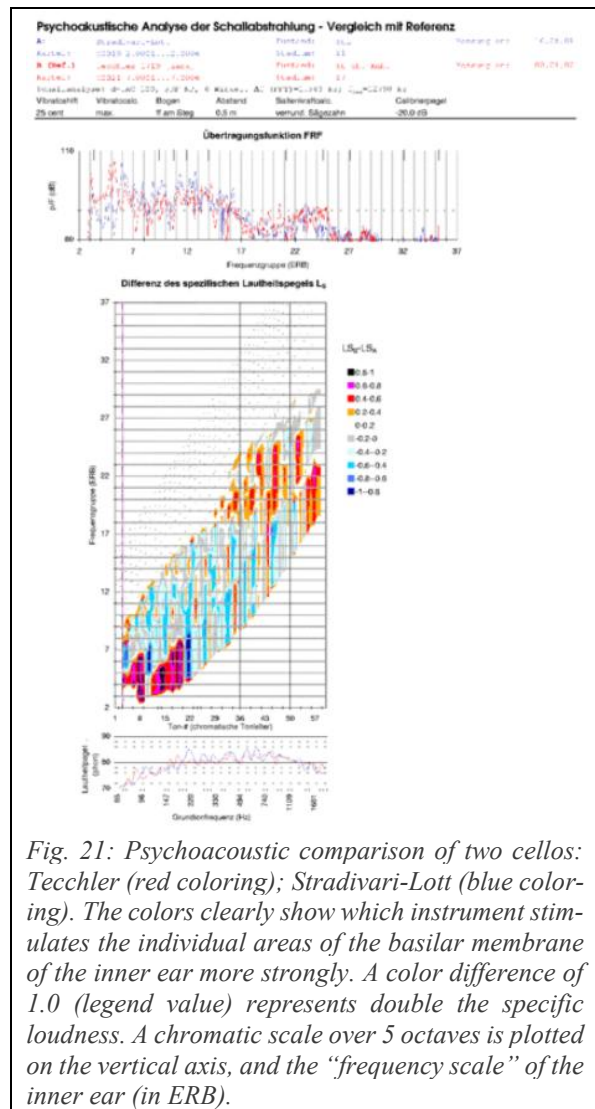


Fig. 21: Psychoacoustic comparison of two cellos: Tecchler (red coloring); Stradivari-Lott (blue coloring). The colors clearly show which instrument stimulates the individual areas of the basilar membrane of the inner ear more strongly. A color difference of 1.0 (legend value) represents double the specific loudness. A chromatic scale over 5 octaves is plotted on the vertical axis, and the “frequency scale” of the inner ear (in ERB).

By adding up the specific loudnesses of all frequency groups, you obtain the total loudness of the calculated bowed tone. This loudness level in phon (which, like specific loudness, takes into account the frequency-dependent auditory perception of the human ear) is shown in the lower line graph in the figure. It can be seen that, despite the differences in timbre between the two violoncelli described above, the total loudnesses of both instruments are relatively similar.

The calculations show that when playing chromatically on one and the same instrument, maximum loudness level differences of about 12 phon occur.

Common to both instruments are the significantly lower loudness levels of the low notes (C and G strings) compared to the notes from the open D string upwards. This “low-frequency weakness” is generally more pronounced in the cello than in the violin. This is because the dimensions of the cello are comparatively smaller than those of the violin in relation to the wavelength of the tones to be radiated. To make matters worse, human hearing sensitivity decreases sharply at low frequencies.

As this example clearly shows, it is not a question of a blanket “good” or “bad,” but rather the specific character of the instrument.

**Example 3:** Differences in sound between two cellos: Francesco Gofriller and Domenico Montagnana (1740).

The following diagram shows the transfer functions of the sound radiation of both cellos, averaged over different spatial directions. Significant main differences concern the two main body resonances (T1 and B1). Both their natural frequencies and the sound radiation levels are higher in the Montagnana cello than in the Gofriller cello. Also striking are the significantly higher sound radiation levels of the plate modes between 1–2 kHz.

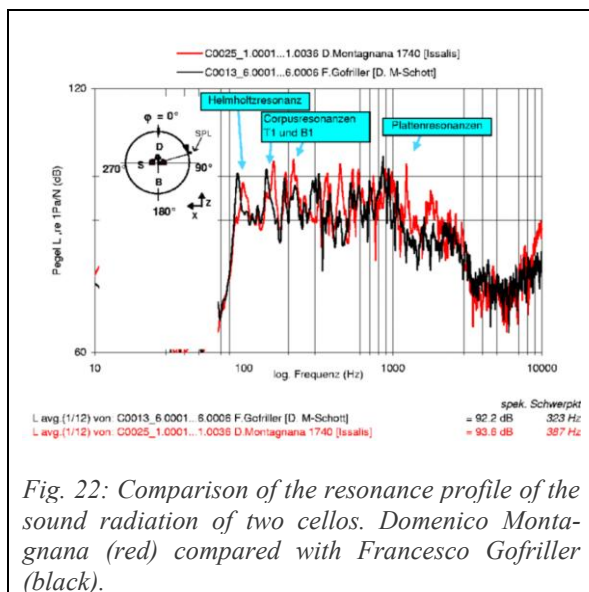


Fig. 22: Comparison of the resonance profile of the sound radiation of two cellos. Domenico Montagnana (red) compared with Francesco Gofriller (black).

The high informative value of the psychoacoustic evaluation of sound radiation mentioned above is particularly evident here. The measured resonance profiles were further processed in the psychoacoustic analysis program. The following illustration shows the result.

The different effects on human auditory perception can be seen in the colored contour diagram in Fig. 23 (“Difference in specific loudness level  $L_s$ ”). The areas in which the Montagnana cello causes greater excitation of the inner ear are shown in red, while those of the Gofriller cello are shown in blue.

This demonstrates the acoustic superiority (greater sound volume, higher dynamic range) of the Montagnana cello: almost the entire area of excitation is colored in shades of red. Only around the 26th frequency group and in the range of the fundamental tones of a few low-frequency individual tones does this Gofriller cello cause stronger specific excitation of the inner ear.

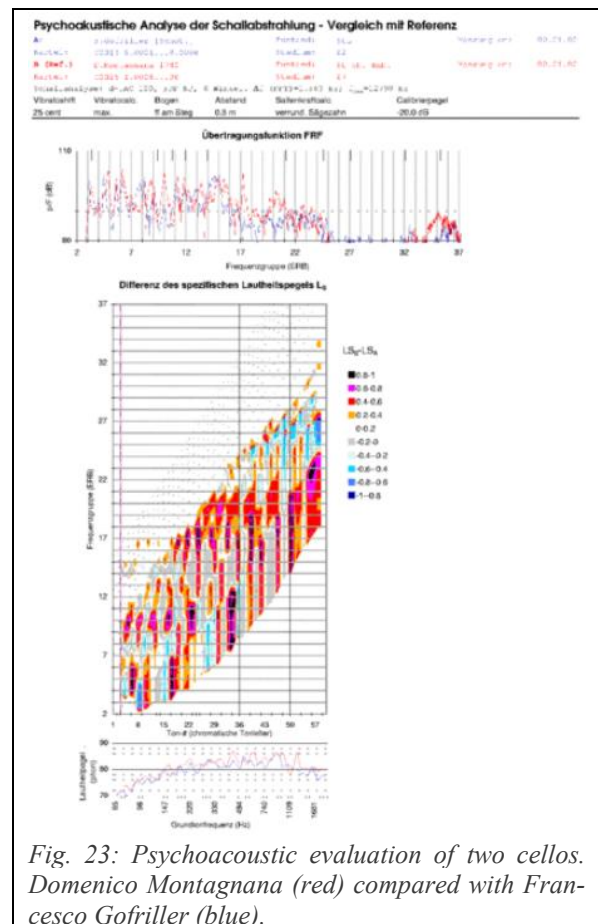


Fig. 23: Psychoacoustic evaluation of two cellos. Domenico Montagnana (red) compared with Francesco Gofriller (blue).

**Example 4:** Sound analysis of a viola (Sannino, Naples, 1906). Method: Measurement of sound radiation using impulse excitation and subsequent calculation of the excitation patterns of the inner ear for all playable individual tones.

The following figure shows the specific loudness (i.e., the excitation perceived by the ear in terms of frequency) of eight different individual tones. The differences in timbre between the open C string and the open D string, for example, are evident. Due to a lack of resonance in the low-frequency range, the fundamental tones of the 1st position C string are practically not radiated. As a result, there is no excitation in the inner ear. The tone sounds less “full” and less “voluminous.” In contrast, the viola develops a large “volume” on the D string. The psychoacoustic evaluation shows strong excitation of the

basilar membrane of the inner ear in the range of the fundamental and first overtone.

This reveals a fundamental weakness of the viola: the ratio of the air wave length of the radiated sound to the size of the body is more problematic for the viola than for the violin. As a result, there is a lack of effective resonances in the low-frequency range of the lowest string.

Due to this lack of resonances in the low-frequency range, the fundamental tones are hardly excited at all across the entire first position of the C string. The strong resonances in the range of the D and A strings, on the other hand, ensure effective radiation of the fundamental tone and first overtone. This produces broadband “sonorous” excitations on the basilar membrane: the instrument sounds ‘full’ and “voluminous” in this range.

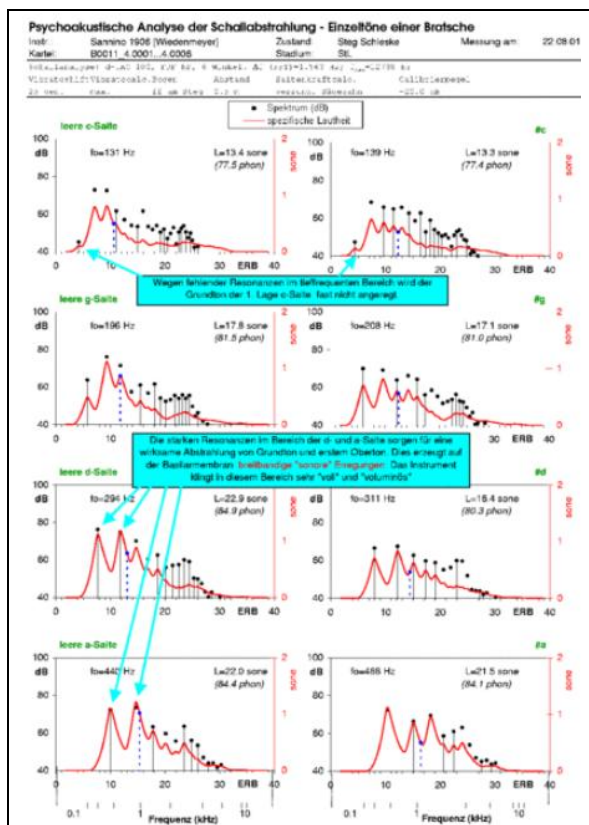


Fig. 24: Viola (Sannino, Bavarian State Orchestra). Eight individual notes are shown: the four open strings (from top to bottom on the left: C, G, D, and A strings), as well as the notes lying a semitone above the open strings (to the right of each).

The following contour diagram fig. 25 shows all 60 notes playable in the viola's range as a specific loudness pattern (inner ear excitation). The x-axis represents the chromatic scale of the 60 semitones, the y-axis the “frequency axis of the ear” (in frequency groups ERB).

The color legend represents the loudness values. Here, too, the “fundamental tone gap” on the C string is clearly visible. Only from the G string onwards are sufficient resonances available for the fundamental tones in the resonance profile of the instrument. The dominance of the fundamental tones can be seen in the lower, colored, upward-curving area.

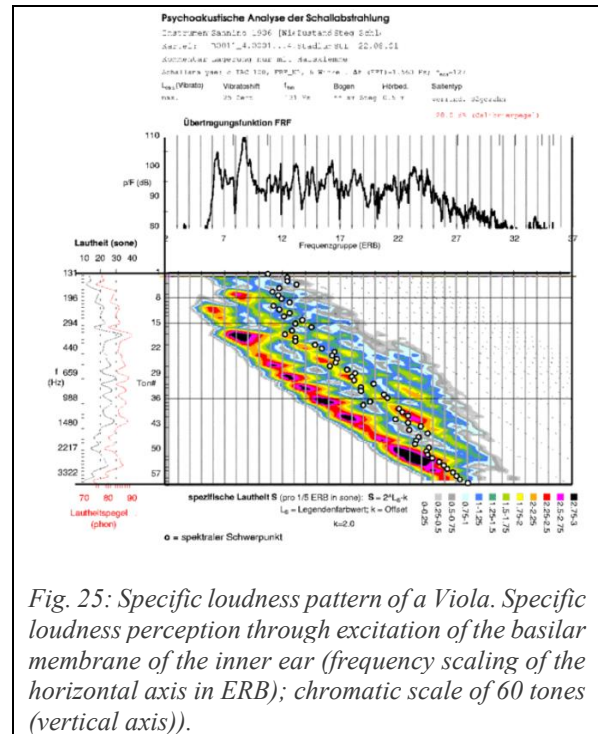


Fig. 25: Specific loudness pattern of a Viola. Specific loudness perception through excitation of the basilar membrane of the inner ear (frequency scaling of the horizontal axis in ERB); chromatic scale of 60 tones (vertical axis).

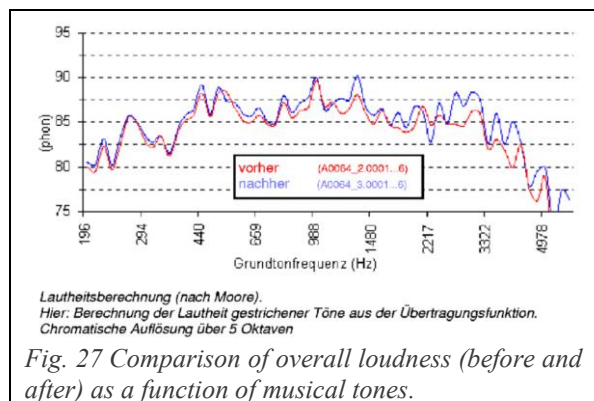
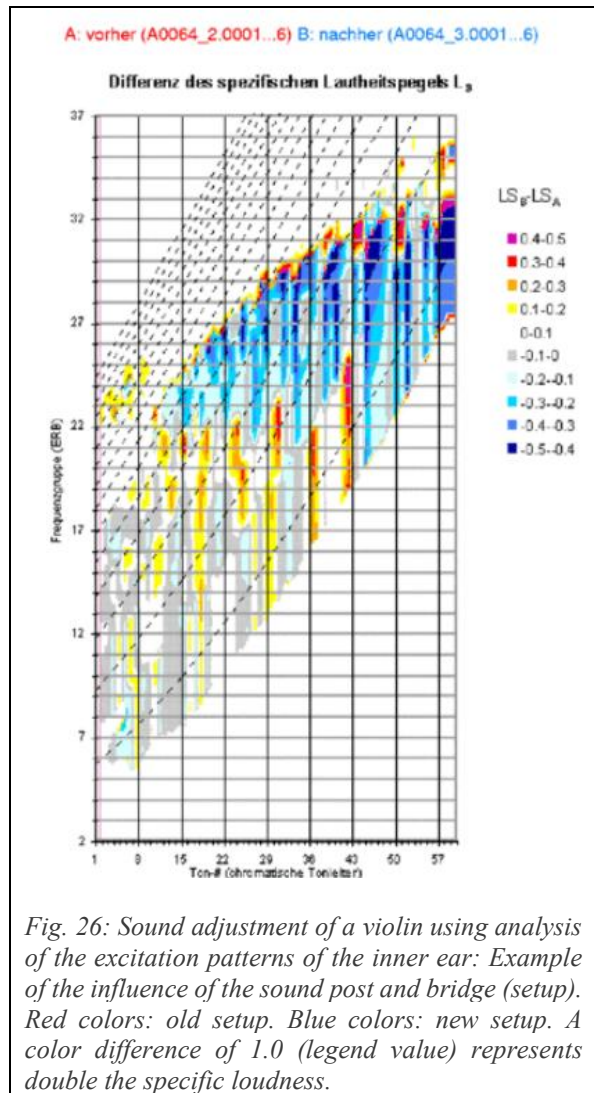
**Example 5:** Sound optimization of a violin using a new sound post and bridge (violin: Sannino).

The psychoacoustic evaluation of sound radiation is a helpful diagnostic tool in the daily practice of violin making for the sound optimization of violins, violas, and cellos.

The violin, whose excitation pattern is shown in Fig. 26, was entrusted to us with a weak E string for sound adjustment. It can be seen that in this spectral range, which is important for the brilliance of the sound, the specific loudness could be increased by almost half.

In the low-frequency range, too, a certain increase in specific loudness was achieved by raising the level of the two main body resonances.

Fig. 27 shows the overall loudness, which was calculated from the specific loudnesses of all bowed notes. As the two curves (before and after) show, the new bridge and soundpost resulted in a significant increase in the soloistic power of the instrument, especially on the E string

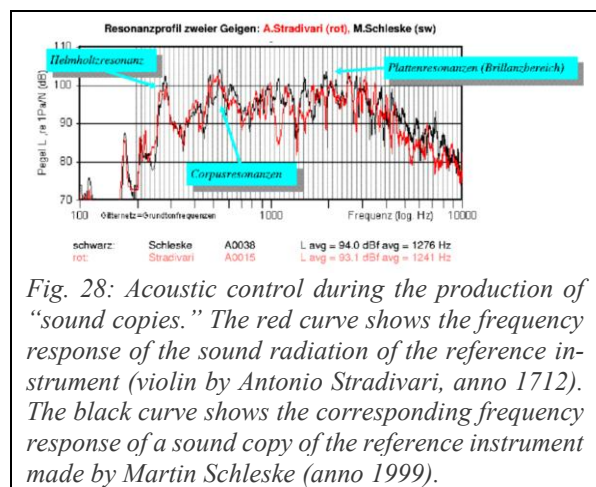


*Explanations for Fig. 27:* The increase in overall loudness achieved is noticeable from the second position on the E string (fundamental frequencies from 1 kHz upwards) with +1..+2 dB. This also noticeably improved the solo qualities of the instrument. The increase in overall loudness achieved is noticeable from the second position on the E string (fundamental frequencies from 1 kHz upwards) with +1..+2 dB. This has also significantly improved the solo qualities of the instrument.

### Example 6: Control during the production of a “sound copy” of a Stradivarius

The fundamental article Martin Schleske: On Making Tonal Copies of a Violin (CAS Journal, Vol. 3, No. 2, Series II, November 1996), which is also available as a PDF in the handbook on this website, describes the procedure for the targeted production of violins whose resonance properties are based on specified reference instruments.

Sound radiation analysis is an essential acoustic control tool in the tonal development process. The results are evaluated psychoacoustically as a final check and documented by supplementary sound recordings.



The aim when making a sound copy is to reproduce the essential characteristics of the individual resonance profile in the development of the newly created instrument. A comparison of the two frequency responses shows that this has been achieved for the characteristic resonance peaks and resonance troughs. Characteristic features are the frequency range and level of the Helmholtz resonance, the pronounced body resonances, the envelope (overall curve) of the plate resonances, and the frequencies of the “notches” between these resonance areas. The energetically averaged overall level of the sound copy (94.0 dB) is slightly higher than that of the Stradivarius (93.1 dB). Similarly, the spectral center of gravity (1276 Hz) is slightly higher than that of the Stradivarius (1241 Hz).

### Example 7: Sound optimization of a cello (Stradivari-Lott) with a new bass bar, tuning peg, and bridge. Analyses performed:

- Modal analysis of the instrument ready to play
- Modal analysis of the free top (Stradivari) with old (not original) bass bar
- Modal analysis of the free top without bass bar

- Modal analysis of the free top with new bass bar
- Resonance analysis of sound radiation before and after sound adjustment

In addition to minor restorations, the following work was carried out:

- Fitting a new bass bar
- Making a new fingerboard
- Correcting the neck angle
- Making a new sound post
- Making a new bridge
- Using different types of strings

The cello by Stradivari and J.F. Lott shown here underwent extensive tonal reworking in our workshop. The original condition was not altered. A new bass bar, sound post, and bridge were made. During this work, comprehensive acoustic and structural analyses were carried out. An example of the numerous individual measurements required for this can be seen in Fig. 30:

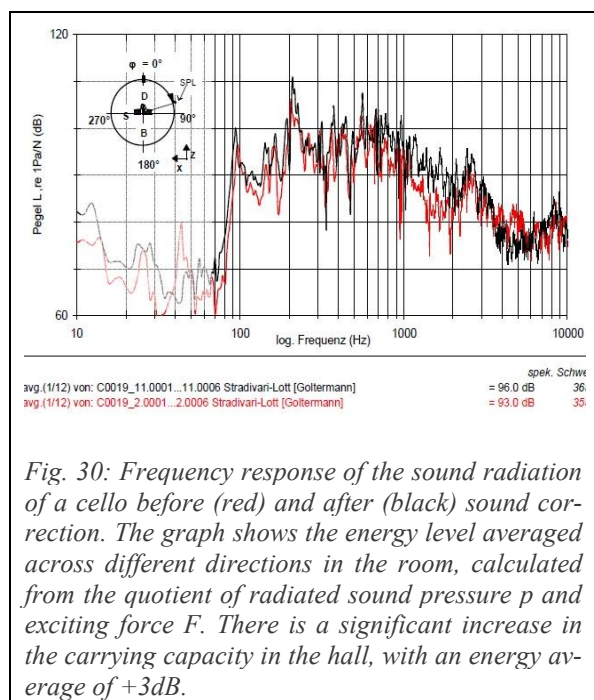


Fig. 30: Frequency response of the sound radiation of a cello before (red) and after (black) sound correction. The graph shows the energy level averaged across different directions in the room, calculated from the quotient of radiated sound pressure  $p$  and exciting force  $F$ . There is a significant increase in the carrying capacity in the hall, with an energy average of +3dB.

It became apparent that the work carried out unleashed considerable additional sound potential in this cello. Fig. 30 shows the frequency response of the sound radiation before (red resonance profile) and after (black resonance profile) the comprehensive sound adjustment. Above all, the increase in the low-frequency resonance range of 100–300 Hz has an extremely favorable effect on the fundamental tone strength of the lower register. The significant increase in sound radiation in the resonance range between 1–3 kHz has enhanced the brilliance of the tone when playing fortissimo close to the bridge and increased the ‘focus’.



Fig. 31: Acoustic analysis in Martin Schleske's master violin-making workshop.

The tonal balance of this instrument has not been altered, i.e., the sound has not become brighter or darker across the board. Beyond the subjective auditory impression, this can be recognized by the fact that the position of the spectral center of gravity (previously 365 Hz, now 355 Hz) has remained largely unchanged.

## LITERATUR

For more information on acoustic resonance analysis in violin making:

Martin Schleske: On Making Tonal Copies of a Violin. CAS Journal, Band 3, Nr. 2 (Serie II), November 1996.

Martin Schleske: Empirical Tools in Contemporary Violin Making: Part II: Psychoacoustic Analysis and the Use of Acoustic Tools. CAS Journal, Volume 4, No. 5 (Series II) November 2002.

## ACKNOWLEDGEMENTS

Recordings and hearing tests as part of the aforementioned EU-CRAFT project were carried out with the support of the Müller-BBM acoustic consulting firm. I would like to express my special thanks to Dr. Karsten Zerbs, Dr. Otto Martner, and Dipl.-Phys. Paul Geißler.

The loudness model underlying my work is based on the work of Professor Brian C. J. Moore, Department of Psychology, University of Cambridge, UK.

## COPYRIGHT

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## APPENDIX: Detailed description of the illustrations

Fig. 1

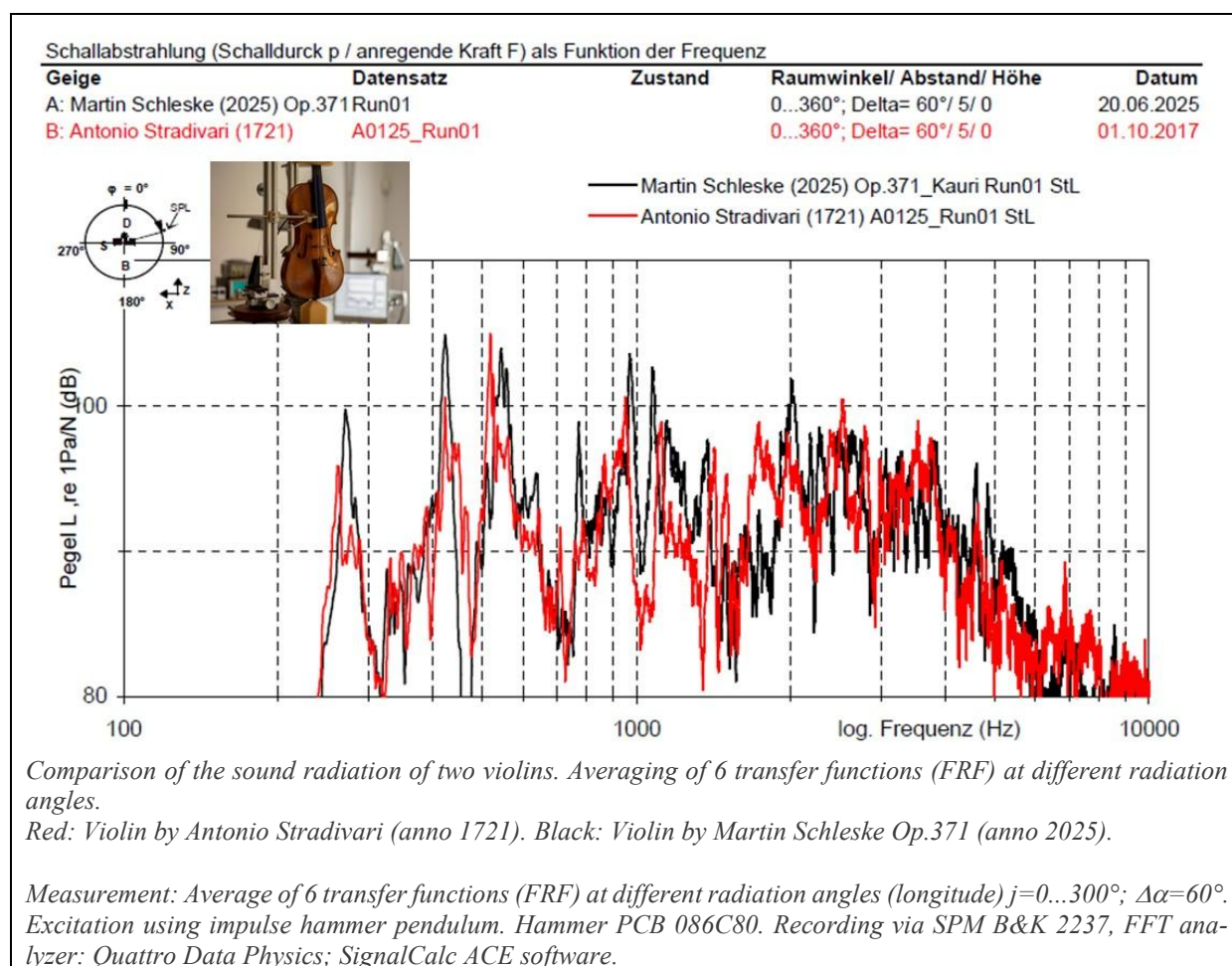


Fig. 2

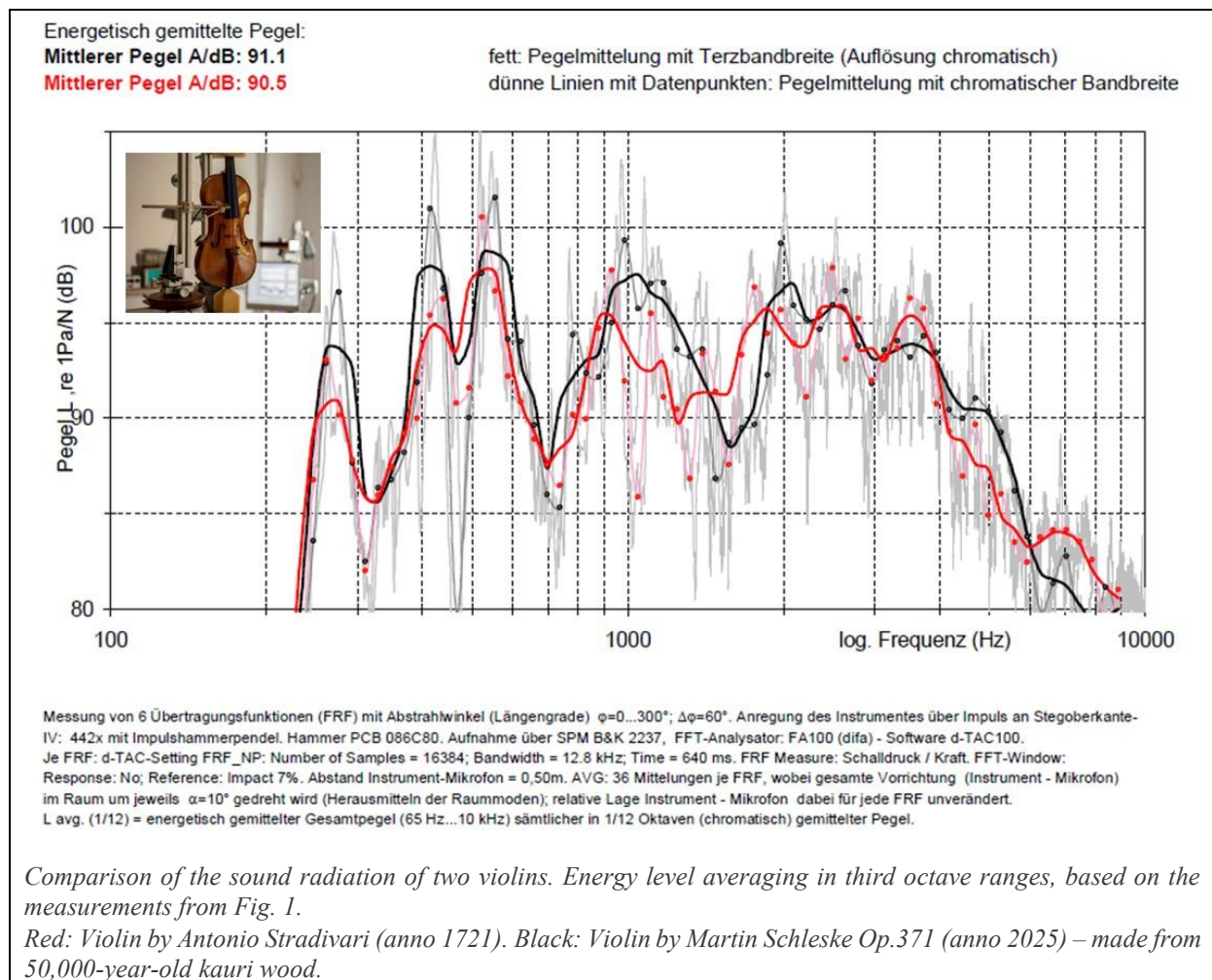


Fig. 3

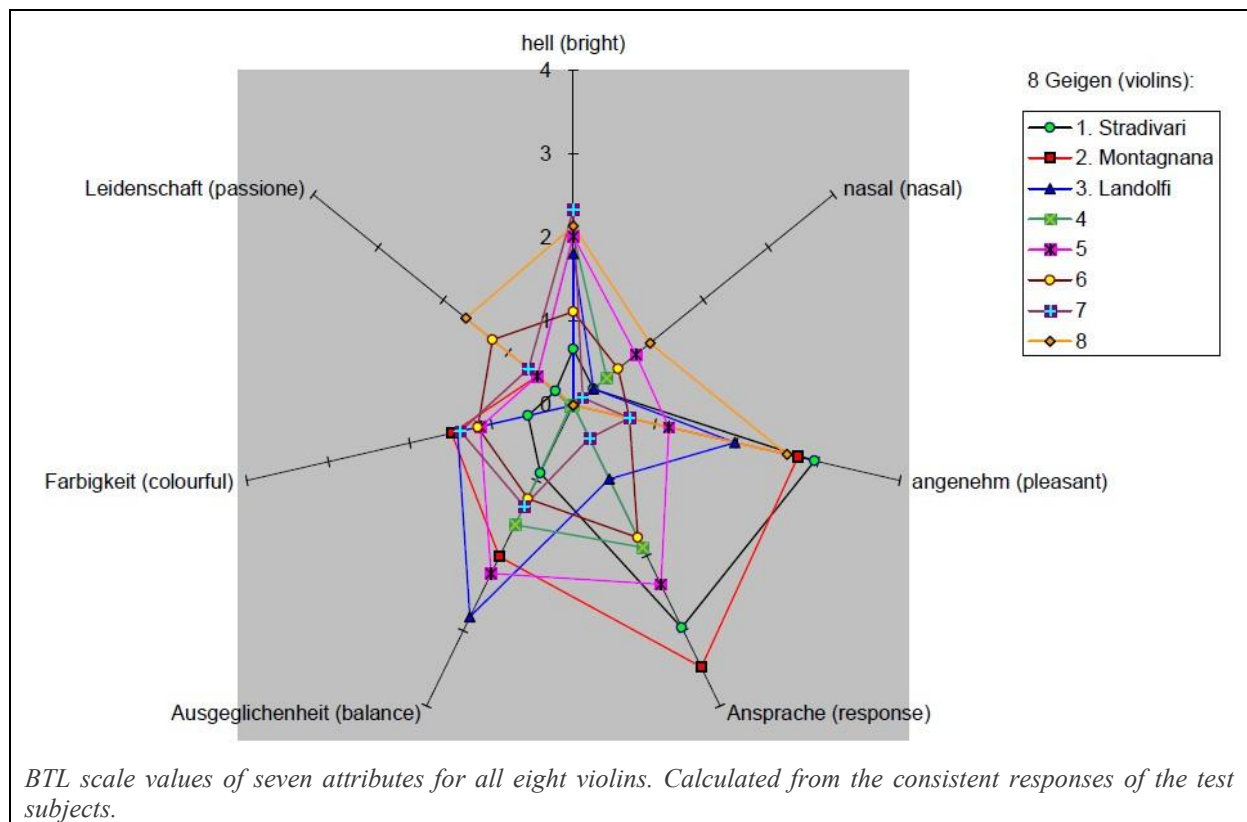


Fig. 4

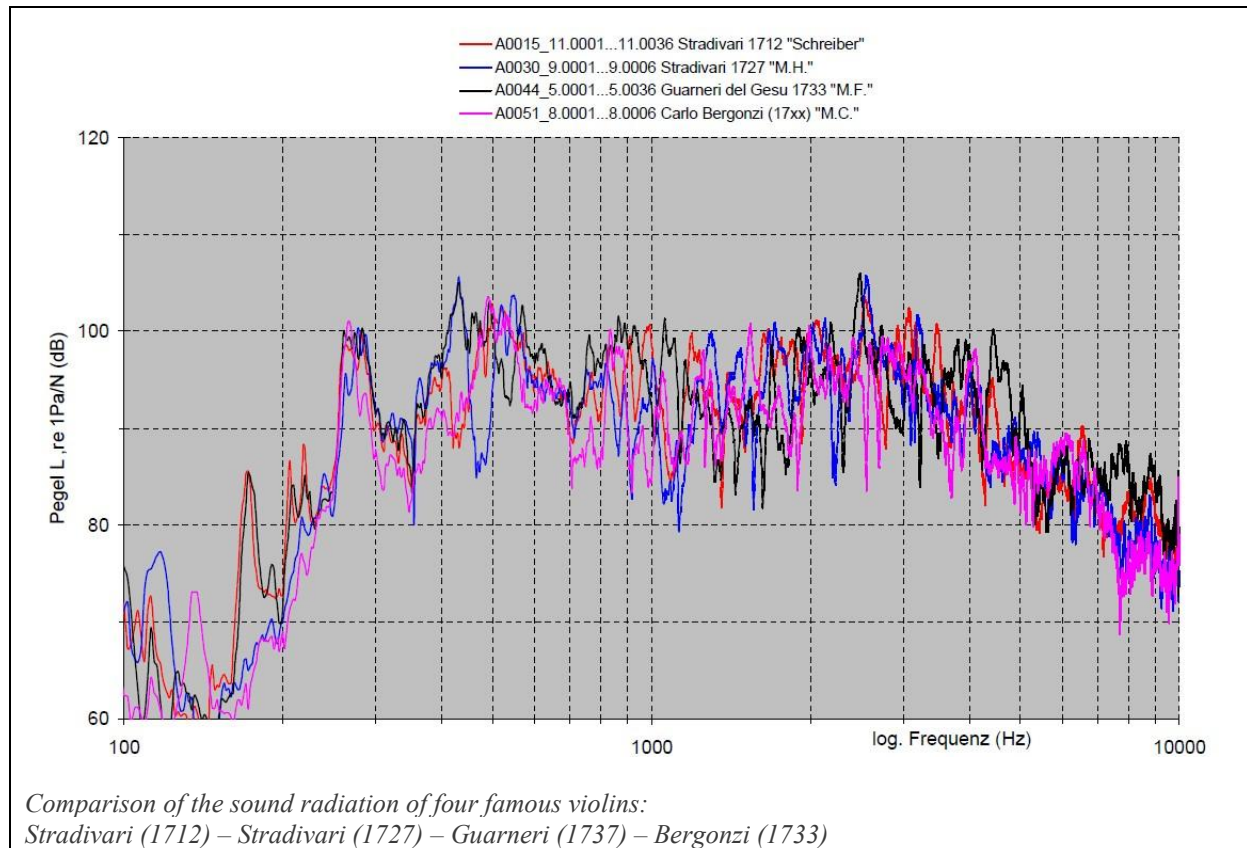


Fig. 6

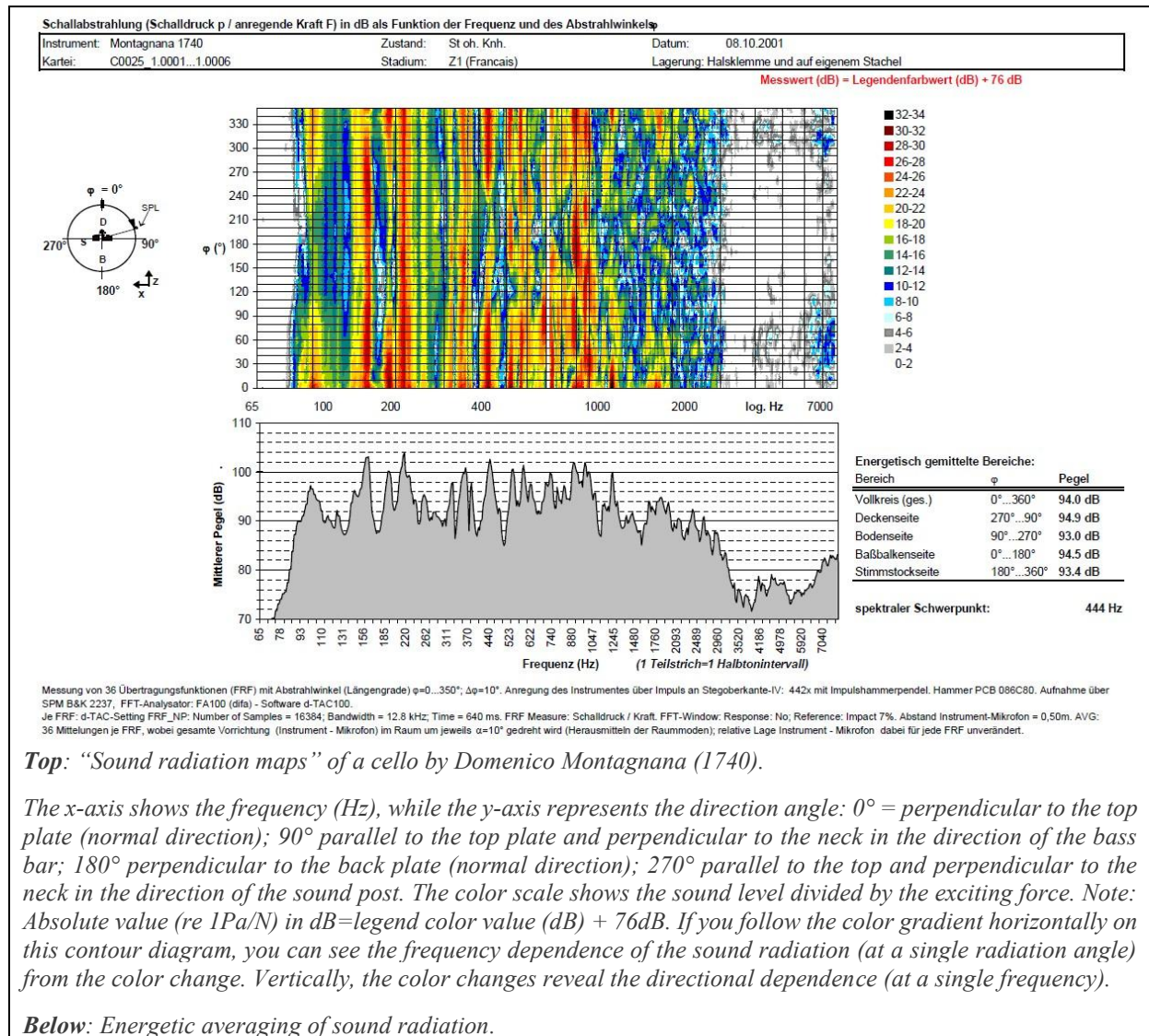


Fig. 9

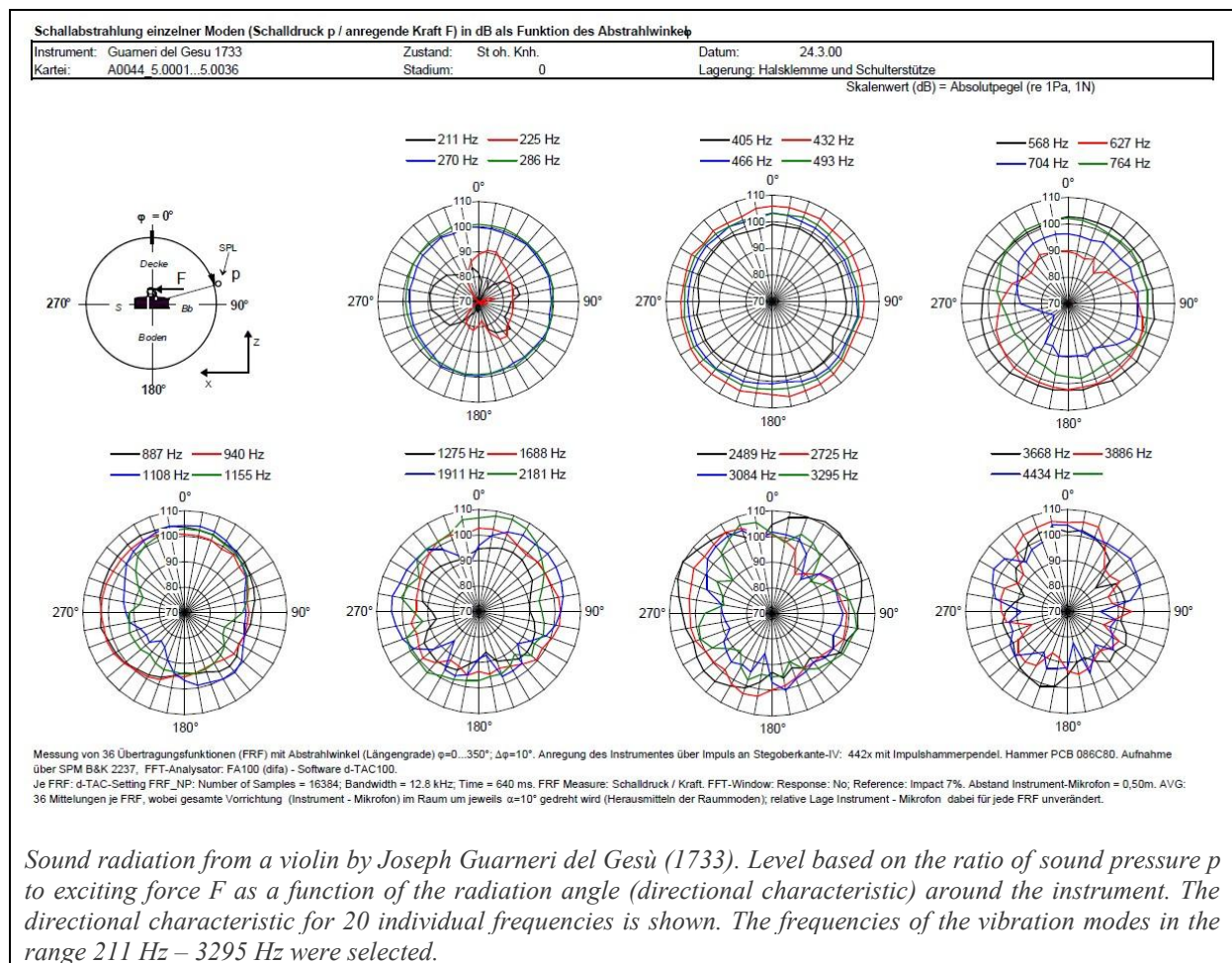


Fig. 10

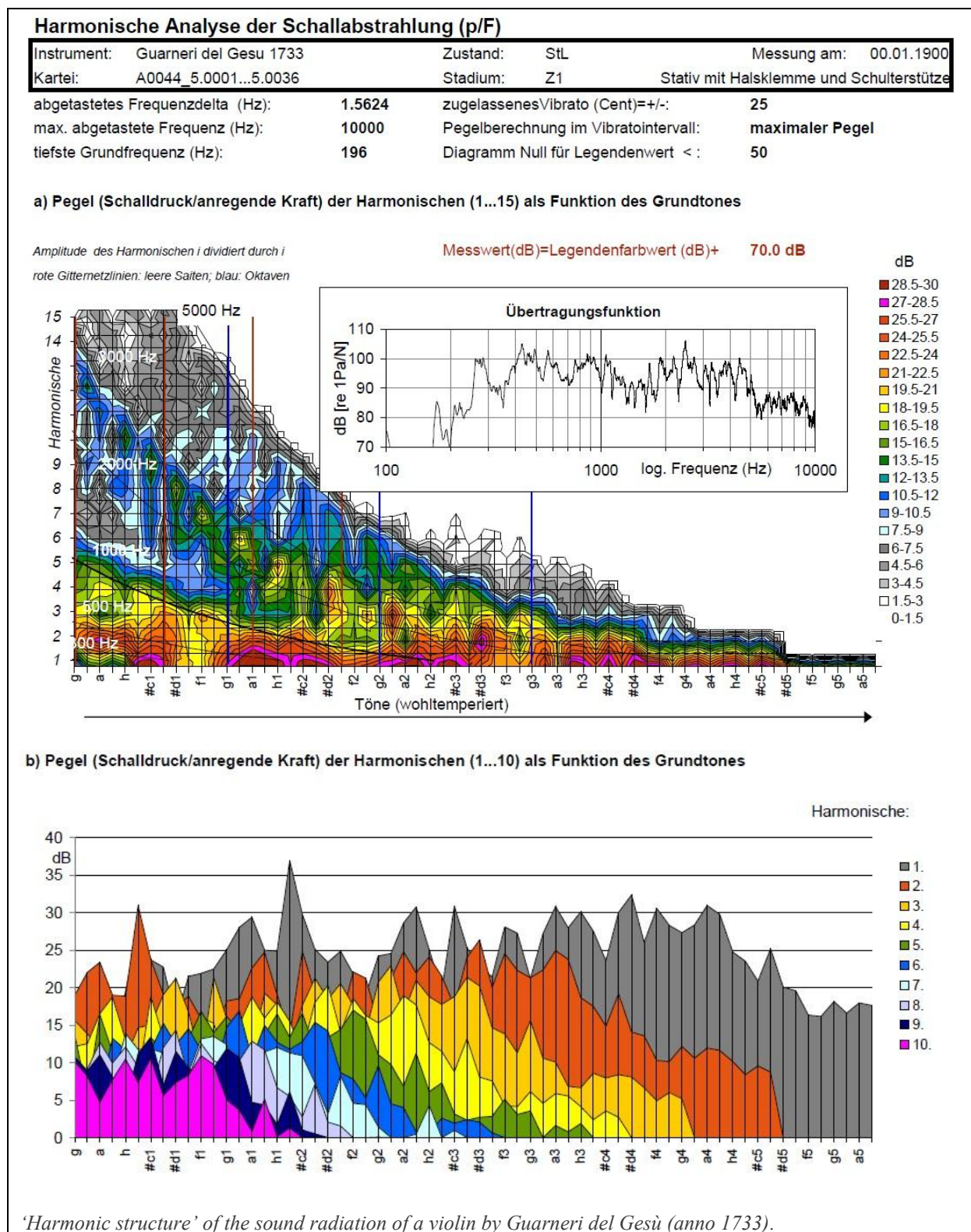


Fig. 12

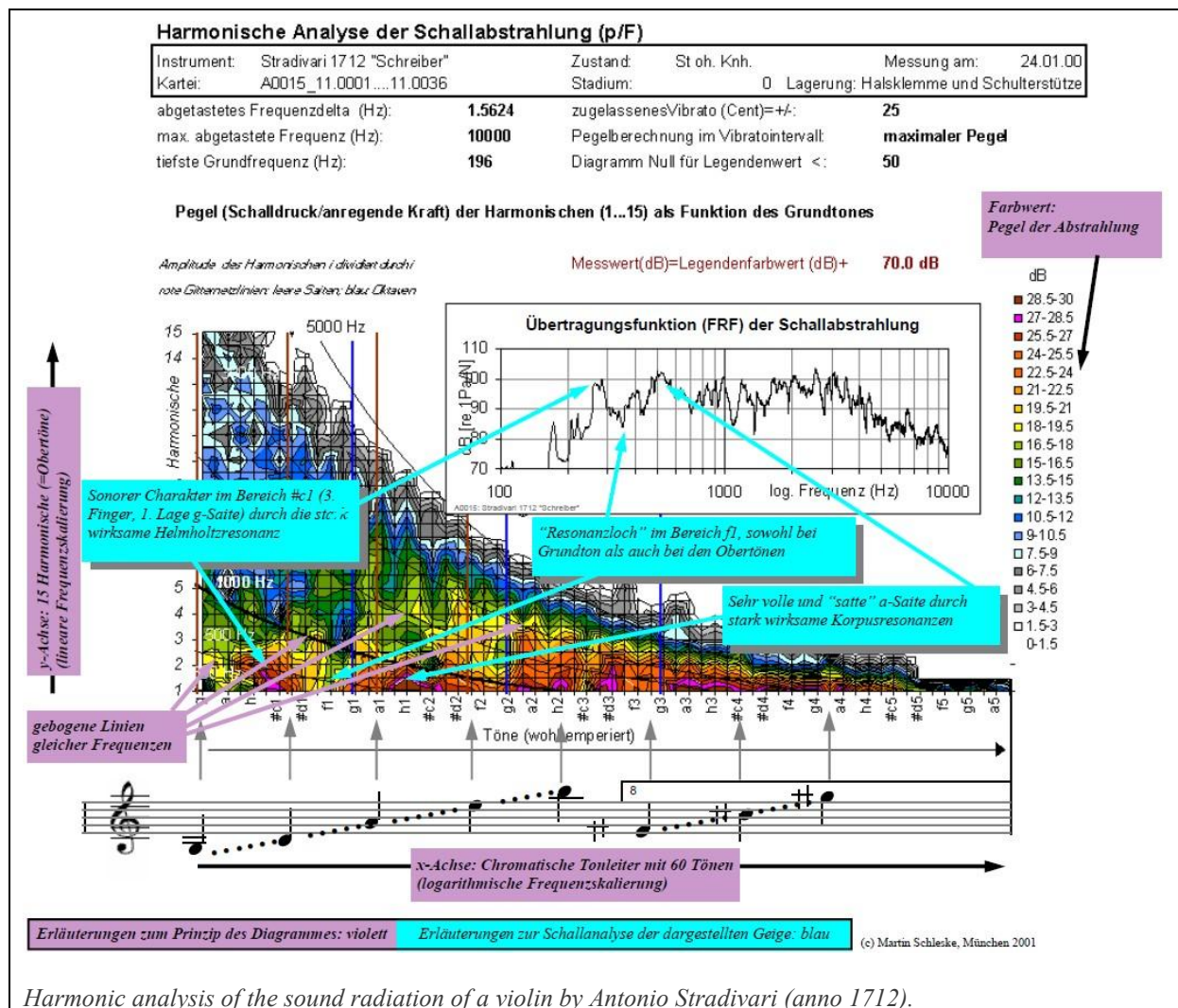
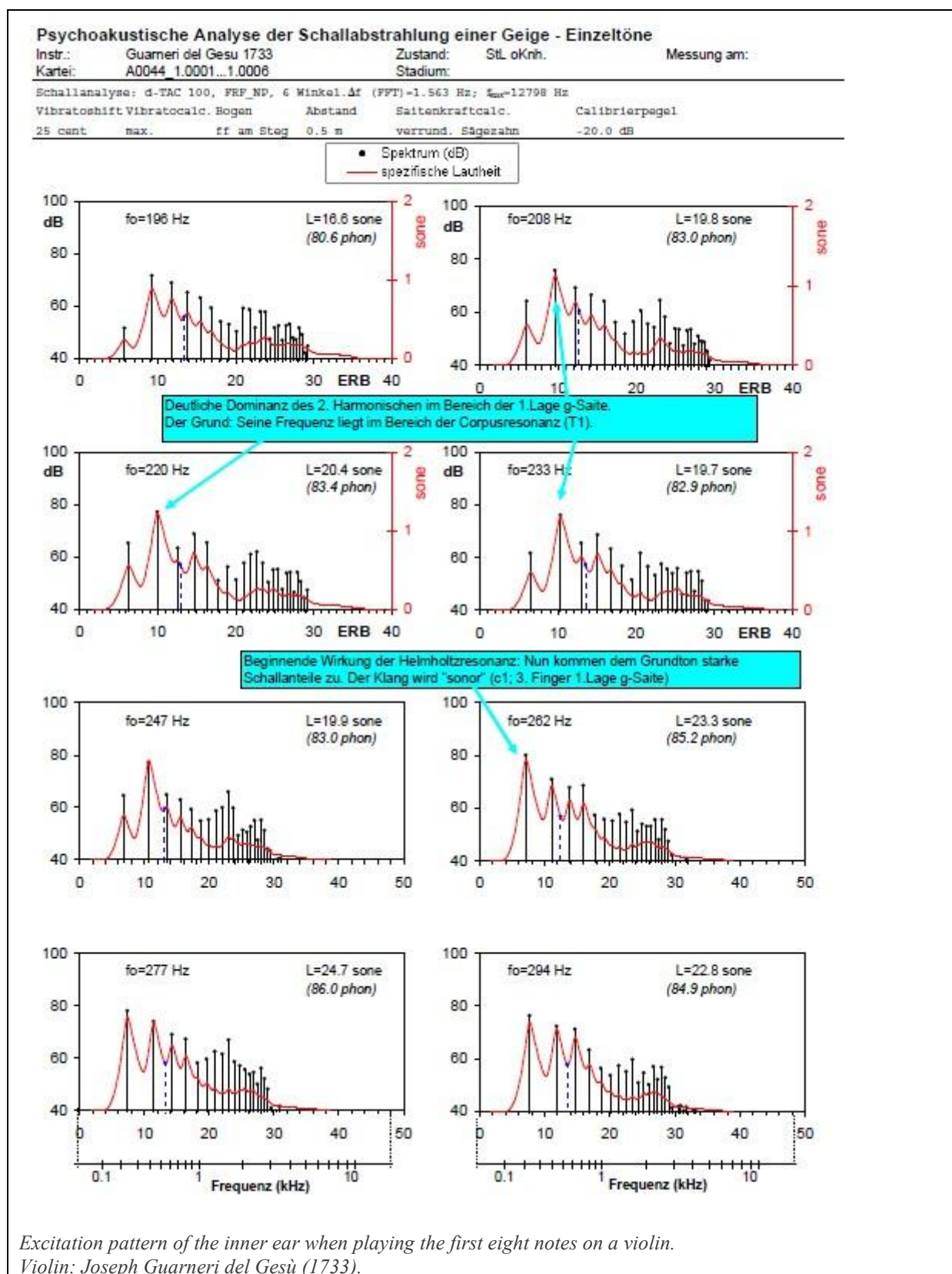


Fig. 13



Excitation pattern of the inner ear when playing the first eight notes on a violin.  
 Violin: Joseph Guarneri del Gesù (1733).

Fig. 14

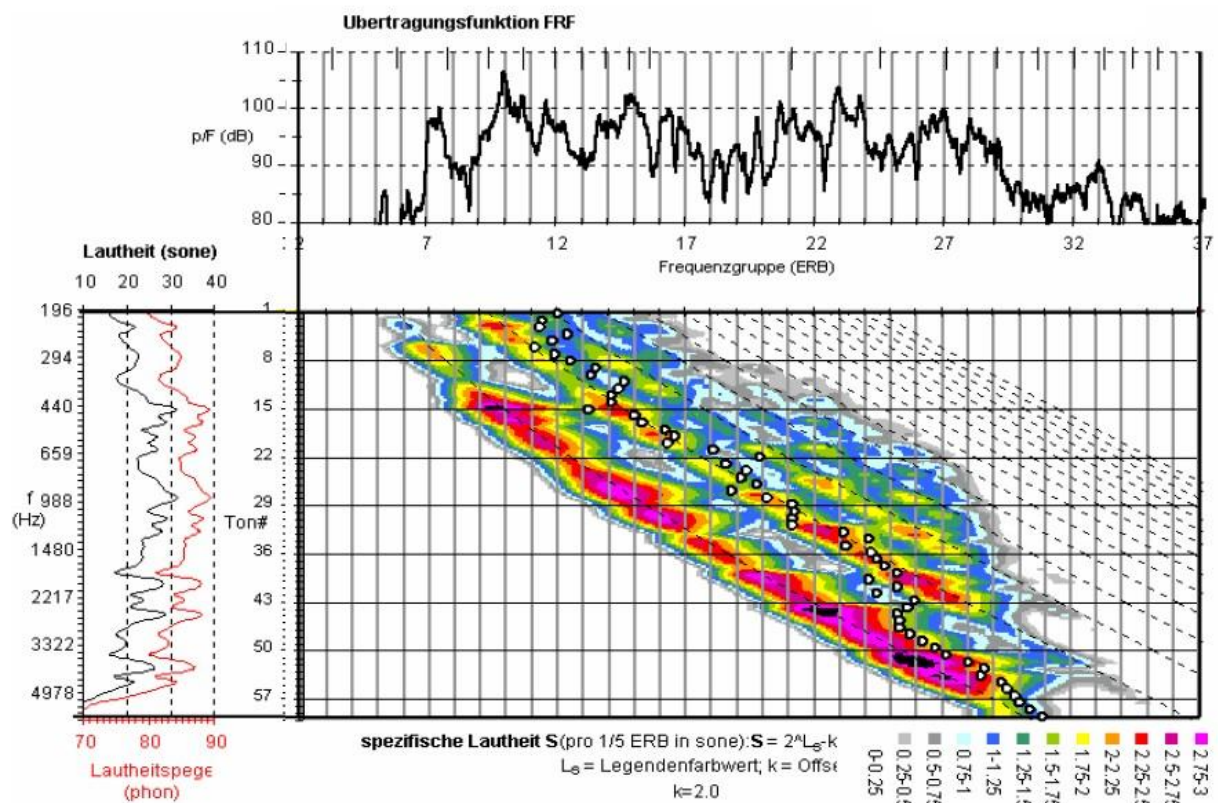
**Psychoakustische Analyse der Schallabstrahlung einer Geige**

Instrument: Guarneri del Gesù (1733)

Kartei: A0044

Zustand: ohne Kinnhalter. Messung mit Halsklemme

Schallanalyse: D-TAC 100. FRF\_NP; 6 Winkel;  $\Delta f = 1.56$  Hz; Lcalc (Vibrato) = max. Vibratoshift = 10 Cent.  $f_{\min} = 196$  Hz  
 Bogen: ff; Hörbed. = 0.5m; Saitentyp = verrund. Sägezahn. Cal. Pegel = -20dB



Psychoacoustic analysis of the sound radiation of a violin. Line graph above: Physical transfer function (FRF). The FRF forms the input variable for the calculation algorithms of the specific loudness.

Color diagram: Specific loudness (in sone) for 60 semitones (chromatic scale).

Line diagram on the left: Total loudness level (in phon) of the 60 semitones.

Instrument: Violin by Joseph Guarneri del Gesù (anno 1733).

Fig. 16

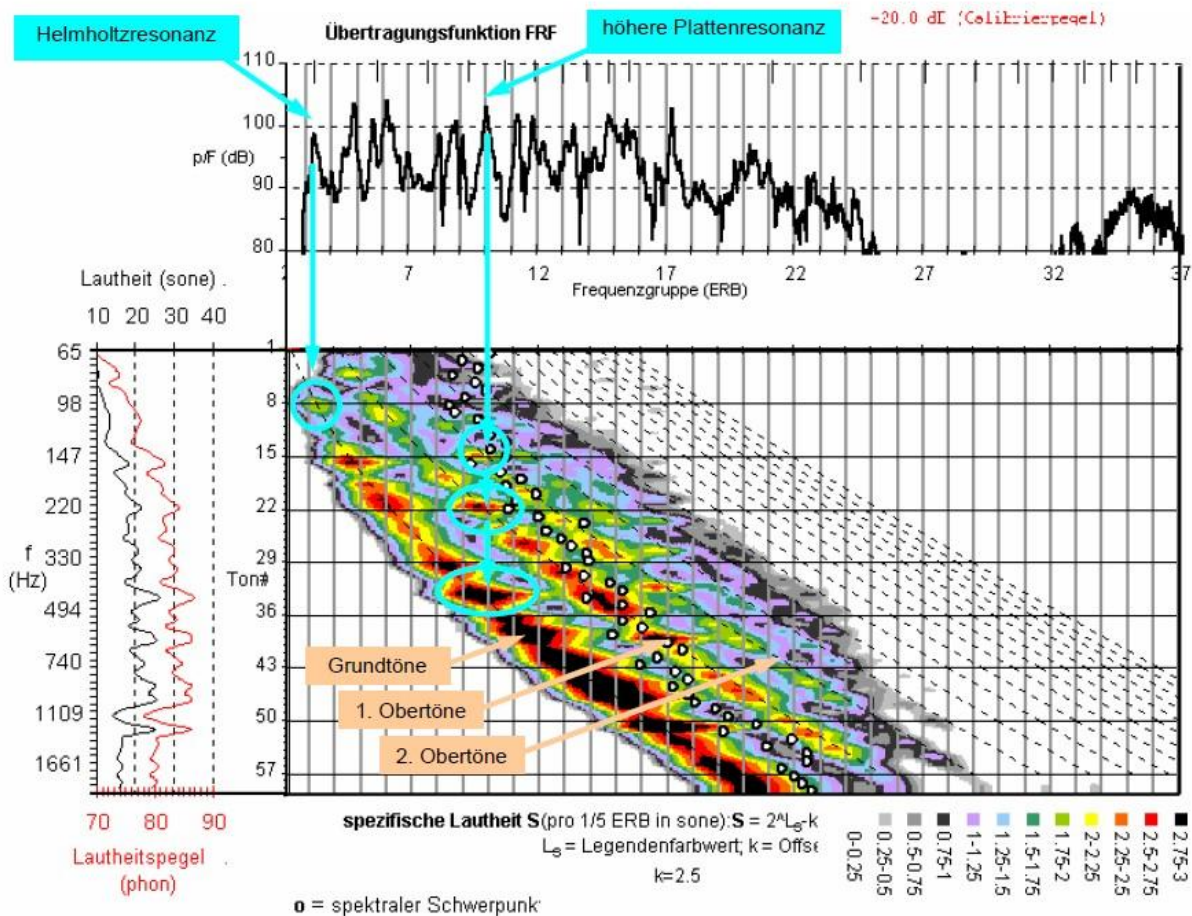
## Psychoakustische Analyse der Schallabstrahlung eines Cellos

Instrument: Domenico Montagnana (1740) „Islerli“

Kartei: C0025

Zustand: Messung auf Stachel mit Halsklemme

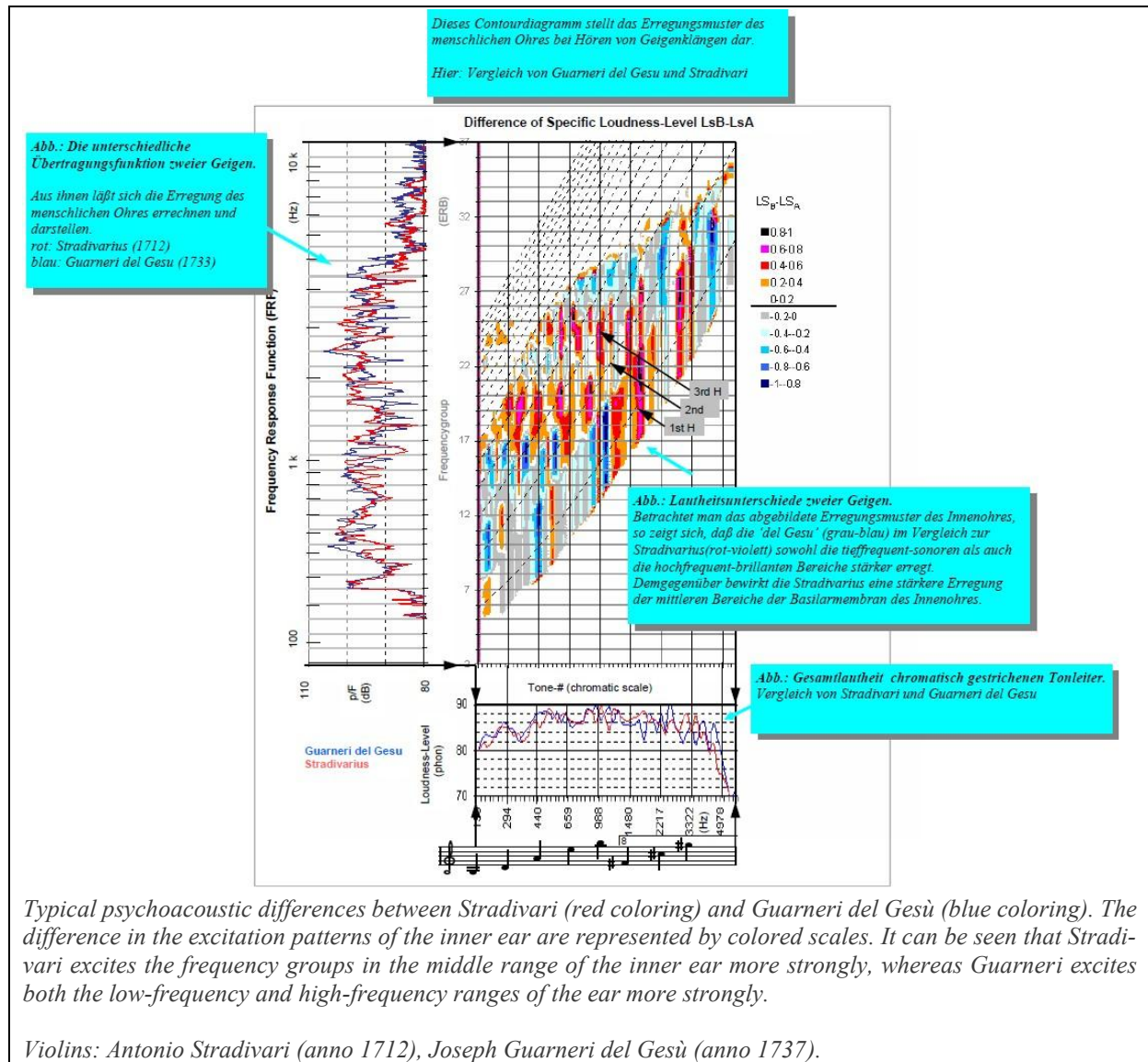
Schallanalyse: D-TAC 100. FRF\_NP; 6 Winkel;  $\Delta f = 1.56$  Hz; Lcalc (Vibrato) = max. Vibratoshift = 10 Cent. f min = 65 Hz  
Bogen: ff; Hörbed. = 0.5m; Saitentyp = verrund. Sägezahn. Cal. Pegel = -20dB



Psychoacoustic evaluation of the sound radiation of a cello. Line graph above: Physical transfer function (FRF). The FRF forms the input variable for the calculation algorithms of specific loudness. Color diagram: Specific loudness (in sone) for 60 semitones (chromatic scale). Line diagram on the left: Overall loudness level (in phon) of the 60 semitones.

Instrument: Cello by Domenico Montagnana (anno 1740).

Fig. 19



Typical psychoacoustic differences between Stradivari (red coloring) and Guarneri del Gesu (blue coloring). The difference in the excitation patterns of the inner ear are represented by colored scales. It can be seen that Stradivari excites the frequency groups in the middle range of the inner ear more strongly, whereas Guarneri excites both the low-frequency and high-frequency ranges of the ear more strongly.

Violins: Antonio Stradivari (anno 1712), Joseph Guarneri del Gesu (anno 1737).

Fig. 30

