PSYCHOACOUSTIC INVESTIGATIONS ON THE POSSIBILITY OF AURALLY IDENTICAL VIOLINS

Paul Geissler[1)], Otto Martner[1)], Carsten Zerbs[1)], Martin Schleske[2)]

[1)]Müller-BBM GmbH, Planegg near Munich, Germany
[2)]Meisteratelier für Geigenbau, Munich, Germany

PGeissler@MuellerBBM.de

ABSTRACT

"Is it possible to make sound copies of violins?" To answer this question one needs to know the ingredients which make two violins judged by musicians to be aurally identical. Using a questionnaire among 54 musicians verbal attributes related to sound quality characteristics of violins were collected and ranked. Subjective listening tests were carried out to check which verbal attributes are suitable and do evoke the same meaning in different persons. Useful attributes for the ranking could be found using statistical measures for consistency and concordance. Additionally, it was found that the measurement uncertainty of frequency response measurements today is smaller than the analysis resolution of the human ear in regard to frequency and amplitude in the frequency range important for the hearing sensation and for room acoustic situations typical for a violin maker's workshop. The results give strong indications that the psychoacoustics characteristics of the human ear and the vibroacoustic characteristics of the violin body in combination with the attributes judged to be important for violin sound quality will in principle allow for the idea of making sound copies of a given violin.

1. INTRODUCTION

1.1. What are sound copies?

Professional musicians sometimes use the sound quality characteristics of a given instrument as a reference and asks the violin maker "Can you make me a violin that sounds like this instrument?". To be even more precise: if the customer holds, say one of the famous old Italian violins in his hand, the question would be "Can you make me a new violin that sounds like this masterpiece in my hand?"

The focus is on the verb "sound". A violin maker learns how to make geometrical copies of masterpieces. This is certainly useful to get a violin body to start with. Of course, due to the differences in the wood material the geometrical copies do in general not sound like the masterpieces.

But if a violin maker is able to build with up-to-date wood material a new violin whose modal characteristics, the eigenfrequencies, damping factors and mode shapes, are identical to the modal characteristics of the reference violin with its old wood material, it should in principle be possible. If the modal identity can be attained, one could expect that the copy also has the same radiation characteristics as the reference violin and hence - for the same listener in the same room - the same hearing impression for both instruments. This concept of modal copies or "tonal copies" has recently been tackled by Schleske [1].

1.2. Can the procedure be simplified?

How accurate must these modal copies be built? Are differences between the modal characteristics of the copy and the reference violin allowed? Taking into account the finite resolution of the human hearing perception and the always present statistical fluctuations in the reverberant sound field of a room one could imagine that the copying procedure can eventually be simplified, if only the differences between copy and reference violin are smaller than the audible differences.

It should also be noted that the question which is formulated here for violins is a fundamental question in sound quality investigations of other products and services as well. The ability to evaluate if two physically not 100% identical products do evoke the same hearing impression for potential customers is the basis for product sound design. Telephone and broadcasting are two branches where simplification procedures based on the human hearing perception have been investigated and applied successfully.

1.3. Acknowledgements

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2. QUALITY ATTRIBUTES

2.1. Questionnaire

The musician's evaluation of a violin is based on a number of perceived sensations and attributes. The sound received at his ears is one of the most important criteria but there are also additional criteria such as playability, reaction of the instrument and others. The interests of the musician certainly play a role, too: Beginners tend to weigh attributes such as playability and reaction much higher than professional musicians. The professional musician usually is much more interested in the sound because he is able to fully control the instrument at hand.

As a first step psychoacoustic investigations were carried out to find out relevant attributes used by musicians for the evaluation of the sound of a violin.

A questionnaire asking for relevant acoustic attributes of violins and the attribute's ranking was designed. The questionnaire was mailed to about 100 musicians in Germany. 54 musicians (26 female, 28 male) sent answers. The musicians were asked: "Please list attributes you would choose to evaluate a violin in respect to sound and playability" and "Please rank the above attributes according to the importance that you personally give them".

For analysis the more than 70 different attributes (or attribute pairs) were grouped empirically into different general features. For example the attributes *bright/dark* (hell/dunkel), *warm/cold* (warm/kalt) or *round/soft* (rund/weich) were grouped to the general feature *timbre* (Klangfarbe), while attributes such as *easy/difficult* (leicht/schwer) or *direct* (direkt) were grouped to the general feature *reaction* (Ansprache). A weight of 1 was assigned to the attribute ranked highest, the second rank was given a weight of ½ and so on.

2.2. Results of the questionnaire analysis

The final result of the analysis, together with some interpretation concerning the correlated physical response quantity, is shown in table 1.

feature	%	physical response quantities correlated
timbre	38	spectral distribution of frequency response
reaction	19	coupling between player and violin
sustain	13	coupling between violin and room
balance	11	balance of spectral distribution
loudness	9	energy of frequency response
modulation	7	dynamic range of frequency response
others	3	color, optics and other attributes

Table 1: *Features, physical meaning and percentile contribution.*

The results show that timbre with a contribution of 38% together with the 11% contribution of balance of timbre are judged by musicians to be the most important criteria for sound quality. Loudness contributes only 9%. Of nearly equal importance is modulation with 7% contribution: a feature that stands for the variability of the timbre and a large dynamical range between forte and piano playing, with the piano passages still markedly above the "operational noise floor" given by the mere bow/string interaction. It is believed that all these features are closely related to the structural dynamic characteristics of the violin itself. These features make a total of 66% of the sound quality features.

Sustain (13%) is judged to be important as well. It is assumed that this feature is related to the coupling between the violin and the room acoustical situation. One could also argue, however, that sustain is for a given room a feature linked with the power of the violin itself. In this case nearly 80% of the features refer to sound quality characteristics of the violin.

A very important feature is reaction which is not a pure listening criterion but takes the feedback of the instrument on the player's action into account. However, this feature is in parts also related to the modal characteristics of the violin. "Other" features (3%) were mostly optical attributes.

The results show that the majority of the selected quality attributes refer to variables linked with frequency response functions. The most interesting frequency response function here relates the sound pressure at the listener's ear to the force at the bridge in bowing direction.

It is important to recognize that there are today psychoacoustic models that allow us to calculate from the measured or calculated sound pressure as a physical quantity psychoacoustic quantities that relate to the various aspects of the hearing perception. For example, for the evaluation of the loudness one has the models of Moore [2] or Zwicker [3], for the evaluation of timbre one has models of Benedini [4] and v. Bismarck [5],[6].

Knowing that we can calculate and evaluate the attributes related to the relevant hearing perception once we know the sound pressure at the ear, it is useful to investigate into the scaling of psychoacoustical criteria and into consequences for the determination of frequency response functions during the violin making.

3. LISTENING TEST

3.1. Setup

Based on the results of the questionnaire a listening test was developed and carried out. Because the main interest here was methodological, the listening test was carried out with only 3 female and 7 male test persons, aged between 30 and 45. It was executed as a complete paired comparison test.

For the listening test the attributes *bright* (hell), *nasal* (nasal), *pleasant* (angenehm), *reaction* (Ansprache), *balanced* (ausgeglichen), *colorful* (farbenreich) and *passionate* (leidenschaftlich) were selected because they were typical for the different features of the questionnaire analysis.

For each of the selected attributes a characteristic sound example was recorded. Sound recordings of 8 different violins played by 2 different professional musicians were made. The binaural recordings were made with an artificial head system. They encompassed short pieces from violin compositions, scales and tones. Using an audio editor short sequences were compiled from these recordings. A time period of 5 seconds duration of this sound was prepared for all eight violins (played by the same musician).

The consistency of the decisions of the listeners was checked. The results showed the difficulties to assess the attributes selected. It was further analysed how the test persons ranked the instruments for all the attributes of interest. As a measure of the concordance between the judgements of different test persons the concordance coefficient [11] was determined. It was found that the concordance coefficient in the ranking was relatively high for the attributes *pleasant* and *reaction*, medium for *bright* and *balanced* and relatively low for *nasal, colorful* and *passionate*.

Not all values were found to be significant on a level of at least 5%, i. e. with an hypothesis error probability $\alpha < 5\%$. Table 2 shows the concordance coefficient for all test persons and for those with consistent answers.

attributes	**W_a**	**α_a (%)**	**W_c**	**α_c (%)**
bright	0.29	0.5	0.45	3,5
nasal	0.18	8.5	0.13	> 40
pleasant	0.68	10^{-5}	0.65	10^{-3}
reaction	0.65	$5{\cdot}10^{-5}$	0.70	10^{-3}
balanced	0.17	20	0.45	3
colourful	0.21	4.5	0.27	> 40
passionate	0.26	1.5	0.72	20

Table 2: *Values for the concordance coefficient W_a for all test persons and W_c for consistently answering test persons (6 or less circular triples, with the exception for passionate: 9 or less circular triples) and values for the hypothesis error probability α_a and α_a, respectively [11].*

The results show that the attributes *pleasant* and *reaction* are rated approximately equal among the test persons. For these attributes the understanding of what pleasant or (good) reaction means was equal among the test persons. On the other hand for *colorful* or *nasal* the value is lower: obviously the understanding of these attributes is different among the different test persons or the test persons had no clear image about these attributes.

For the scaling of the ranking evaluation the BTL-method [12] was chosen.

The results for the BTL-scale based upon the consistent decisions is shown in the following table 3 and figure 2.

violin	**bright**	**nasal**	**pleasant**	**reaction**	**balanced**	**colorful**	**passionate**
no. 1	0.67	0.31	2.96	2.96	0.90	0.55	0.27
no. 2	0	0	2.75	3.48	2.02	1.49	0.55
no. 3	1.81	0.31	1.98	0.98	2.81	1.42	0
no. 4	2.04	0.52	0	1.89	1.59	0.03	0.55
no. 5	2.02	0.96	1.17	2.38	2.24	1.14	0.55
no. 6	1.12	0.69	0.69	1.76	1.24	1.17	1.24
no. 7	2.34	0.14	0.69	0.44	1.34	1.38	0.69
no. 8	2.14	1.48	2.62	0	0	0	1.65

Table 3: *BTL – scaling values, calculated from the cumulated preference frequency of the consistently answering test persons.*

According to table 3 violin no. 1 is not particularly bright (0.67) but sounds very pleasant (2.96) and has a good reaction (2.96). On the other hand violin no. 7 is ranked to be very bright (2.34) but ranked low for pleasant (0.69) and reaction (0.44). Table 3 also shows that the violins in the test have no significant difference in the ranking concerning the attribute nasal.

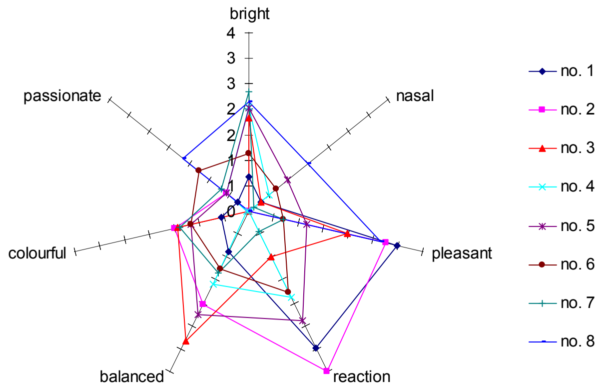

Figure 2: *BTL-scaling values of consistently answering test persons for violin no.1 to 8.*

The results are to be interpreted from a methodological perspective. They show that one can find attributes like *pleasant*, *reaction*, *bright* and *balanced* that do evoke approximately the same meaning within different persons. They are obviously not only important but can additionally be used for scaling and ranking of the sound quality of different violins, whereas attributes like *passionate, colorful* or *nasal* evoke a different understanding in different persons. They can not be properly scaled properly and should therefore be omitted for the ranking of violins.

4. FREQUENCY RESPONSE FUNCTIONS

The above results show that the majority of features is implicitly described by the frequency response characteristics of a violin, measured e. g. as the frequency response function of the sound pressure at a specific point in the room (e. g. at the listener's ear) related to the force input at the bridge in bowing direction. Conceptually such a frequency response function can be subdivided into the structural frequency response functions of the acceleration or velocity of various points on the violin body in normal direction related to the force input at the bridge, and the vibroacoustic frequency response functions of the sound pressure at the specific point in the room related to the accelerations or velocities at the violin body.

How accurate must the frequency response characteristics of the copy meet those of the reference? It is known that the sound pressure frequency response level of a room, when it is excited by a sinusoidal sweep, shows irregularities due to the overlap of the modes and phases. Cremer and Müller [10] showed, based on results from Kuttruf and Thiele [8] and Schröder [9] that the number of level maxima n_R in a given frequency band Δf can be written as

$$n_R = \frac{T}{6.7}\Delta f \qquad (1)$$

with T being the reverberation time of the room.

From this result on can estimate the number of level maxima in the 1/12-octave centered around a halftone f_H, n_{RH}, to be approximately $n_{RH} \cong 0.009{\cdot}Tf_H$.

In a concert hall with a typical reverberation time of 2 s this results approximately in 4 level maxima for the band around the lowest tone of a violin (G3, $f_H \approx 200$ Hz) and 115 level maxima for the band around the highest tone, five octaves above the lowest tone, (G8, $f_H \approx 6400$ Hz). For a reverberation time of 0.5 s – which is typical for a small living room or a violin maker's workshop – one would have about 1 level maximum per halftone at 200 Hz and about 29 maxima per halftone at 6400 Hz.

A violin has typically only 1 mode, the so-called Helmholtz-resonance, in the frequency range 200 Hz to 400 Hz. The number of level maxima per halftone for a violin, n_{VH}, in this frequency range can be estimated from the above result to be approximately $n_{VH} \cong 0.0003 \cdot f_H$. For 400 Hz this number is 0.12. It is considerably smaller than the number of level maxima for a room. Therefore it is important to match the Helmholtz-resonance of the copy exactly to the Helmholtz-resonance of the reference violin.

For frequencies between 400 Hz and 800 Hz one usually observes 2 to 4 modes in frequency response curves of sound radiated from violins. For 4 modes the number of level maxima per halftone would be $n_{VH} \cong 0.0006 \cdot f_H$. For 800 Hz one would calculate the number of level maxima per halftone to be roughly 0.5, which is still smaller than the equivalent number for rooms. The exact matching of eigenfrequencies in the copy is important in this frequency range, too.

The exact matching of eigenfrequencies becomes less important, however, when $n_{VH} \geq 1$, i. e. when there is at least one mode in the violin body per halftone. Estimates based on the modal density of a 5 mm flat plate indicate that this happens at about 1500 Hz. Woodhouse reports similar results based on estimates of modal overlap factors [13], and observations from mobility measurements show that the transition frequency where $n_{RH} \geq 1$ can be even lower. Above approximately 1500 Hz the exact matching of single modes is not very important as long as the overall modal density and damping are preserved.

The limits in the resolution of human hearing can be stated by the so-called just-noticeable sound changes. Data for just-noticeable sound changes vary to a certain extent between different authors. In [7] it is stated that the just-noticeable relative frequency difference for pure tones between the 500 Hz and 2000 Hz octave presented to a listener for 500 ms or longer is roughly 0.002 x frequency, i. e. about 2 Hz around 1000 Hz. For octaves below 500 Hz and above 2000 Hz these values are larger. Also, for a shorter duration of the tone presentation – which is likely when one evaluates the sound quality of different violins - these differences increase and are for a duration of 10 ms approximately 10 times higher than the values stated above, i. e. 20 Hz around 1000 Hz. Concerning the sound level it is stated that the just-noticeable level difference for white noise is about 0.5 dB for levels above 25 dB.

With an optimized measurement procedure, using a hammer pendulum system, one is able to measure frequency response functions, including the radiated sound pressure, up to 3 kHz with an uncertainty of 0.5 dB (and from 3 kHz to 10 kHz with an uncertainty of 2 dB). The frequency resolution is typically dependent upon the measurement time but can be selected so that the frequency resolution is smaller than the above mentioned just-noticeable changes.

5. CONCLUSIONS

It was shown that there are sound quality features of violins that a relevant for musicians and do evoke similar perceptions in different listeners. These features can be scaled and used for consistent sound quality ranking of violins. The features can be analyzed from measured frequency response functions using psychoacoustic models. For frequencies below 1500 Hz the modal characteristics of the "tonal copy" and the reference violin must be identical or very similar. For higher frequencies the average modal density and damping must be preserved. The uncertainty of the frequency response measurement is smaller than the just-noticeable changes of our hearing perception. Thus a violin maker can in principle measure the modal characteristics of the copy for the final instrument and during the working progress and evaluate if the sound quality is already "near enough" – i. e. aurally indistinguishable - to the reference violin. It is very clear that these results do not make violin making easier, because it needs intuition, professional experience and excellent workmanship to select the correct starting geometry and to continuously control and tune the modal characteristic of the violin.

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