Proceedings of the Institute of Acoustics

ON THE KINETICS OF SPICCATO BOWING

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1. ABSTRACT

A skilled performer is able to play a series of spiccato strokes (i.e., producing short notes by means of a bouncing bow) with each onset showing little or no aperiodic motion before a regular slip/stick pattern (Helmholtz motion) is triggered. Kinematic analysis reveals that a well-behaving bow gives nearly vertical impacts on the string, and that the first slip of each note takes place when the normal bow force is near its maximum. The complex movement of the stick can be decomposed into a translational and a rotational motion. The translational movement starts with a straight-lined downward/backward shift (for down bow) and returns in the same path with an upward/forward shift for the next attack. Within this cycle, the bow describes two periods of rotational motion with the finger grip (thumb and the opposite fingers) near the axis of rotation. This paper discusses the relation between the quality of attacks and the phase relation between these two motions.

2. INTRODUCTION

Spiccato (from Italian: spiccare: "clearly separated, cut off") is a bowing technique where the player lets her bow bounce on the string, once per note, to create a series of notes with crisp attacks followed by freely decaying "tails". This effect was not easily achieved until François Tourte (1747-1835) started making bows with concave curvature of the stick, quite opposite to the earliest musical bows, which were convexly shaped (bending away from the hair). In order to combine a quick attack with a longer (off-string) decay, the necessary bow force must be very quickly established and terminated. The Tourte bow could manage this well, because it did not tend to fold or collapse like the older ones did. However, stiffness alone was not enough to produce good-quality spiccato. A very precise timing in the complex bow manipulation is also imperative. In fact, the quality of spiccato differs greatly even among professional string players today.

3. THE PHASES OF A "PERFECT" SPICCATO

Figure 1 shows a computer-simulated "perfect" spiccato as performed on an open violin G-string (196 Hz). The main control parameters, bow velocity (v_B) and bow force (f_Z), are included in the diagram, which shows the string velocity at the point of excitation. While v_B changes like a sine function around zero, f_Z is programmed as a clipped ($f_Z \geq 0$) offset cosine function with twice the frequency of v_B. The string velocity pattern clearly shows Helmholtz triggering (i. e., only one slip per period) after the initial release at (a). During the interval (a-b), the string amplitude builds up quickly until, at (b), the bow force is so small that the string motion starts decaying exponentially due to natural damping of the string with terminations. This state lasts until (c), where f_z starts rising again, but now - combined with the lowered v_B - it forces a quick decay of the string velocity. At (d), the limiting static frictional force is high enough to keep the string from slipping while brought over to the opposite side of the equilibrium line. This prepares the next release in the opposite direction. Thus each note can be subdivided into five phases (intervals a-b, b-c, etc.), all of which seem necessary for producing a crisp clean spiccato.

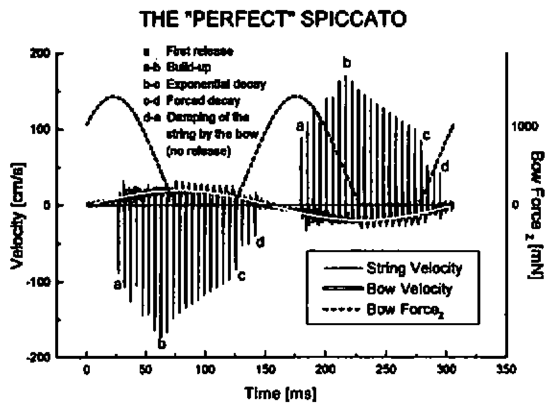


Figure 1:
The "perfect" spiccato can be subdivided in four phases (see text). The string velocity pattern is produced through simulation of an open violin G-string.

Figure 2 (below):
During spiccato, the movement of the bow can be decomposed in translational and rotational motions. The center of rotation lies close to the player's thumb on the frog.

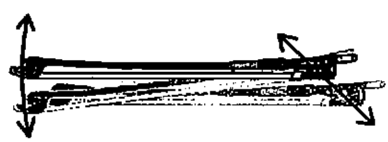


Figure 2 shows the two components of the bow motion which are necessary to create the desired combination of v_B and f_z. The straight arrow at the frog indicates a translational movement with the frequency of v_B. At the tip, a rotational movement is indicated. The center of this rotation lies somewhere at the frog, close to the player's right-hand thumb, while its frequency is that of f_z, i. e., twice the translational one. For the player, the challenge lies in the phase coordination of these two components.

Figure 3, where three combinations are compared, illustrates this point. In the upper graph, the cosine function, representing force, is applied without any lag ($\alpha = 0$). The bow force decreases too early, and starts its second increase long before v_B has descended to a low value. This results in a double buildup for each note, and the string amplitude will never reach a high value: the impression is a "choked" spiccato. In the middle graph, f_z is given a -53^0 lag compared to the velocity. This produces the "perfect" spiccato which was shown in Figure 1. In the lower graph, the lag is -107^0. Of its four attacks, two are "scratchy" with multiple flybacks and irregular and poorly defined onsets (#2 and #3). The two remaining attacks show clearly longer buildup times than in the perfect case. The explanation should primarily be sought in the lack of forced damping which did precede the initial slips in the middle graph. For $\alpha = -107^0$, remaining Helmholtz components of high amplitudes and "wrong" (opposite) phase orientation are still present when v_B changes sign.

Figure 3:
Computer simulations of spiccato with three different timings between the bow-velocity cycle (full sine wave) and the bow force cycle (clipped cosine wave). Only the middle case produces a "perfect" spiccato.

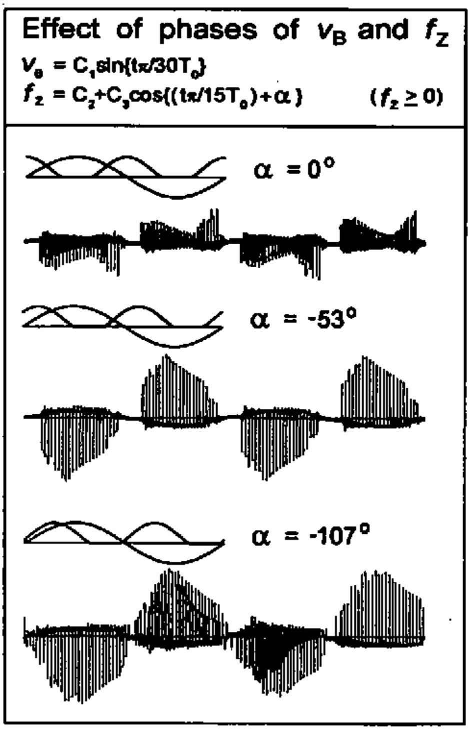
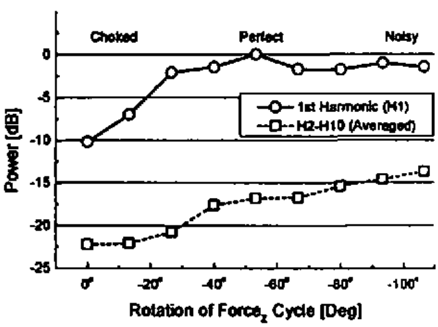


Figure 4 (below):
Power output obtained in nine spiccato simulations with different timing between bow velocity and bow force. Each simulation consisted of 30 attacks. The attacks could be played back after convolution with a suitable transfer function: bridge force - radiated sound. The last three simulations on the right-hand (noisy) side included many "scratchy" attacks that appeared randomly in spite of the consistent control of the bowing parameters (bow velocity and bow force).



The graphs in Figure 3 were taken from a simulation series with nine sets - each consisting of 30 attacks - in which alpha was changed from 0^0 to -107^0 in intervals of 13.33^0. The force on the bridge was taken as the output of the simulation, and convolved with a transfer function obtained by recording a force impact on a violin bridge and the resulting sound pressure picked up by a microphone 30 cm away from the violin body. This convolution gave a signal with the characteristics of the sound of a real violin, and the quality of the spiccato could then be judged by listening. Out of the nine simulation sets, only one alpha produced perfect attacks for all 30 notes. With $\alpha = -40^0$, there was one noisy attack, while all sets with $\alpha < -53^0$ gave many noisy attacks appearing randomly. For the sets where $\alpha > -53^0$, all sounded choked, but less so as the lag of -53^0 was approached. Figure 4 shows the arithmetic average of the decibel values of harmonics 2 through 20 as compared to the levels of the 1st harmonic. Not surprisingly, the "perfect" spiccato gives the highest 1st-harmonic power, while $\alpha = -107^0$ gives the highest average power for the partials.

The results of the simulations do not imply that $\alpha = -53^0$ is a magic figure. The "magic" lies elsewhere. A perfect attack requires a few initial periods with a gradually increasing v_B combined with a f_z that does not change too rapidly (say, less than 5-7% per nominal period). With the bow-force function in Figure 1, this leaves f_z with a marginal area of about $\pm 20^0$ to 30^0 around its peak value, during which the initial periods must be triggered. In this case, the first release occurred -9^0 after the force maximum. With a slightly higher v_B, the first release would have occurred earlier, but perfect attacks might still have been produced. Figure 5 (from Guettler 1992 [1]) shows conditions for perfect onsets when f_z is kept constant.

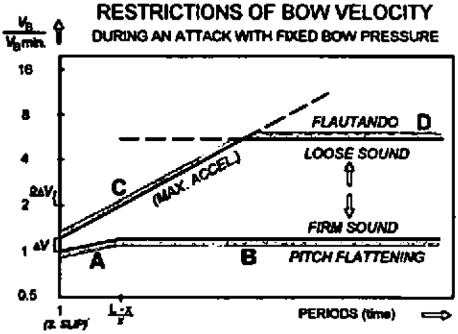
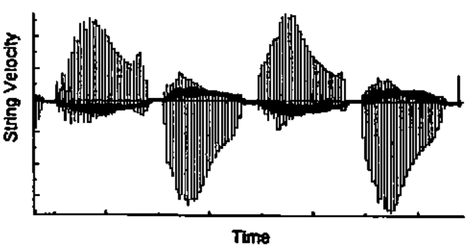


Figure 5:
During an attack with fixed f_z, the bow velocity should follow a path inside the frame of A through D in order to create Helmholtz motion as quickly as possible (Guettler [1]). At the onset, only a narrow range of bow velocities will produce Helmholtz triggering (one flyback per period). After a few periods, the tolerance for bow velocity and bow force is much greater.

4. MEASUREMENTS OF SPICCATO BOWING

Figure 6 shows recording of string velocity during spiccato performed on a violin D-string by a professional string player. The measurements were done by applying a miniature magnet close to the bowing point, and recording the voltage across the string. The three last notes are perfect in timing and triggering, while the first one displays a premature increase of the bow force, causing a few periods to grow in amplitude again. In between the attacks, "quiet" areas exist.

Figure 6:
String velocity at the bow, recorded during spiccato on a violin D-string. The patterns compare well to the figures obtained through simulations. Notice the quiet intervals between notes. All four are nearly perfect. In the first attack the bow has returned a little early after the "exponential decay", causing the amplitude to rise again. A good professional player is capable of producing a series of spiccato notes with little or no onset noise.



Without direct measurements, some information on the magnitude of the bow force can be gained from the ripple of the velocity signal. Due to the relatively low Q-values of the torsional string modes, the ripple (which mainly consists of transformed torsional waves) will fade quickly when the bow is off the string. Figure 7 shows the second attack in Figure 6 analyzed in the same manner as in Figure 1. In the interval (a-b) the ripple is growing due quick buildup of flybacks [2]. In the interval (b-c) the ripple is decaying, which means that f_z is zero, or close to zero. Between (c) and (d) the ripple grows again although the transversal amplitude is still decreasing. This is an indication of bow-string contact, which seems to be a necessary condition for torsional-transversal transformation to happen [3]. After (d), static friction reigns, and the bow damps all remaining string vibrations very efficiently.

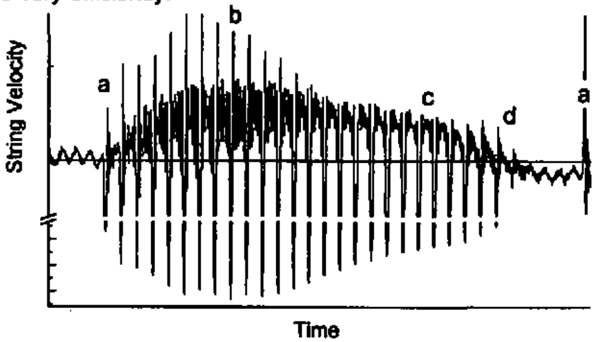
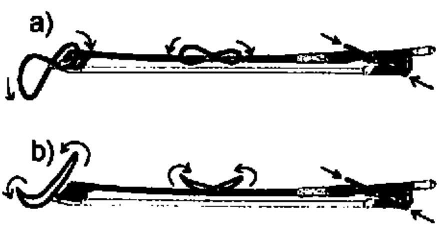


Figure 7:
Some information on the bow force can be extracted from the ripple in the velocity signal. Using the same marking as in Figure 1, the letters (a) through (d) are placed where the interpretation of the ripple signal makes changes in bow force plausible (see text).

5. VISUAL FEEDBACK FOR THE PLAYER

The easiest way to determine the phase conditions while performing the spiccato, is to put small marks on the stick and watch the figures they make. Figure 8 shows two of several possible patterns. During a high-quality rapid spiccato, the stick midpoint will always describe a sideways eight (∞ the infinity symbol), like the example in Fig. 8(a). Then the stick will be approaching the string at the end of each stroke and a forced decay take place. If the pattern is shaped like a V or a U, the attacks are always noisy because the bow is off the string whenever it changes direction. In Figure 8(b), the rotational motion is delayed -108°, compared to (a). (The figures are drawn out of proportions for clarity.)

Figure 8:
An easy visual way to confirm the phase relation between the translational and the rotational movement during rapid spiccato, is to put a small white mark on the middle of the bow stick to see the pattern it describes. Of the two patterns shown here, only (a) will produce a crisp sound. In (b), the attacks will be noisy because the change of bowing direction takes place when the bow is off the string. When the bow returns to the string, remaining Helmholtz components of high amplitudes and "wrong" (opposite) phase orientation will still be present. In (a) the hair has contact with the string during the bow change, thus muting these waves.



6. CONCLUSIONS

A well-performed spiccato requires a high degree of precision between the rotational and translational components of the bow motion. The rotational component has the same frequency as repetition rate of the attacks, while the translational component has only half that frequency. When measuring the displacement of the bow stick in the bowing direction (y-plane), and in the direction of the normal bow force (z-plane) by means of two accelerometers, their trajectories are predominantly sine waves with frequencies corresponding to the translational and rotational components, respectively.

A crisp spiccato with little or no attack noise can be separated in four parts: (1) "the buildup", starting with an initially high bow force combined with an increasing bow velocity, followed by a rapid decrease in bow force after a few initial periods. (2) "the exponential decay", with decreasing bow velocity and little or no bow force. (3) "the forced decay", with the bow still moving (slowly) in the "old" direction while the bow force builds up again, with the effect that the string amplitudes are quickly reduced. (4) "the muting of the string", during which the bow force is great enough to prevent the string from slipping while the bow changes direction in preparation of a new string release.

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Proceedings of the Institute of Acoustics

LISTENERS' JUDGEMENTS AND ACOUSTIC PROPERTIES OF VIOLINS

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INTRODUCTION

The existence and function of the so-called singer's formant has been described in numerous publications and seems to be unquestioned by now. Singing and string instruments are similar not only in terms of physics, but also in the historically developed sound ideal and the necessity of sound projection in large concert halls [1]. On this background, this investigation aims at testing the hypothesis that an overtone region equivalent to the singer's formant should be responsible for the dominance and 'carrying power' of good violins.

A small number of violins was selected. The selections was made on the basis of the instruments' origin and measured frequency curves. The frequency curves (see Figure 1) were measured in an anechoic room (Technische Hochschule Aachen) by Dünnwald using his electromechanical excitation device [2].

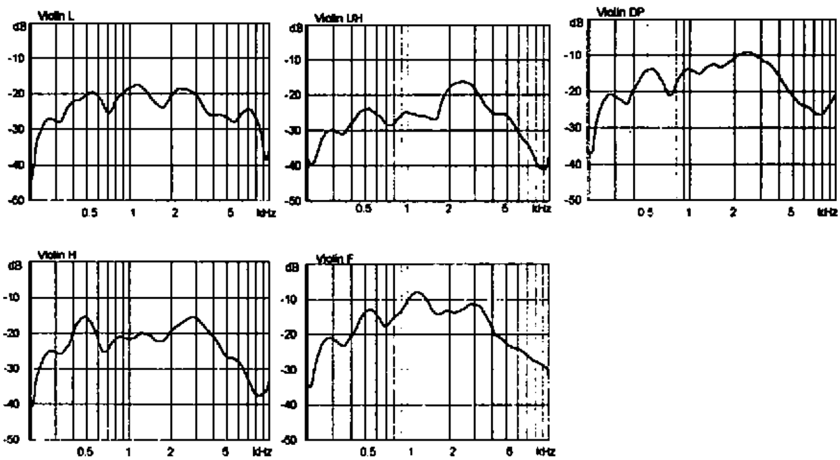

Figure 1. Smoothed frequency curves of 5 violins selected for the tests. Violin L: old French violin labelled "Nicolas Lupot 1815", concert instrument of player H.: Violin UH: 18th century bohemian, unknown violin maker, sometimes used by player H.; violin DP: new violin by H Dünnwald; violin H: new violin by hobby violin maker; violin F: factory made violin named "Conservatory Violin Straduarius".

Only violins L and H are used in professional or amateur music performances. The selected violins show clear differences and partial similarities in the following features:

There is a clear concentration of spectral energy in the frequency region between 2 and 4 kHz in each curve but the amplitude is different in relation to the rest of the curve: Violins UH and DP show amplitude predominance of the frequency region in question, violins L and H have nearly equal amplitudes of the other or the lowest frequency regions, while violin F is characterised by predominance of a middle frequency region (around 1.300 Hz). On the assumption that frequency curves measured in the anechoic room correlate with the spectra of the same violins played in concert halls it should be possible to test the hypothesis of the singer's formant by appropriate listening tests. Up till now, two tests were made on the basis of live violin playing, and several others on the basis of the recordings of these live performances. In all cases each violin was played in a pair with each of the other violins by two professional violinists. The listeners were placed in two groups in the front (5 - 6 m from the stage) and in the rear (25 m from stage) of the concert hall.

In both live tests the listeners were asked the following questions:

1. Which violin (of the pair) sounds better?
2. Which has more "carrying power" (Tragfähigkeit)?

Despite the fact that no definitions of "sound quality" and "carrying power" were given and the number of listeners in test no. 1 was very small (14 in both groups) the results could be interpreted and used for the design of subsequent tests.

RESULTS OF TEST 1

(12 December 1996, University of Cologne assembly hall)

Two professional violin players (H: concert master; S: female member of orchestra) played

(a) a tone sequence in g-major: g - b - d' - g' - b' - d" - g"

(b) the beginning of M. Bruch, Violin Concerto.

The following diagrams show the correlation of two experimental conditions: front vs. rear position in the audience (Figure 2) and player S. vs. player H. (Figure 3).

The answers were evaluated as follows: The preferences of each instruments over all other instruments in all possible pairs (except identical instruments) were summed up and given in per cent of possible answers. In Figures 2 and 3 the answers referring to quality and carrying power were summed. With two exceptions (*) the correlation between the factors of position and of player is relatively high. The exceptions cannot be explained satisfactorily but in both cases the judgement of quality is strikingly poor for the two phrases played by S. The diagrams show two distinct groups: Violins L, H, and DP were given more than 50 % preference and obviously constitute one group as opposed to violins UH and F. The correlation of quality ratings with carrying power ratings presents a clear picture if the values for front vs. rear position and for player H. vs. player S were averaged. Except for violin UH, Figure 4 shows a strong correlation of the subjective parameters in question. Leaving the explanation of the role of violin UH aside it is evident that quality and carrying power constitute one parameter of subjective judgement. In the light of recent investigations [2] the interpretation of the clear subjective ranking in terms of their frequency curves seems plausible only in the case of violin F (factory made): The dominance of the frequency region from about

1 kHz to 1.3 kHz is correlated with unpleasant, nasal attributes of sound. As to the contribution of the potential singer's formant (2 - 3 kHz) of the frequency curves, there does not seem to be any plausible interpretation. Especially in view of the frequency curve of violin UH we have to assume that there may be a considerable difference between the frequency curve (measured by electromechanical excitation of the treble side of the bridge) and the spectra of the violin as played in the test. Amongst other factors, this assumed difference may be due to the fact that different parts of the bridge are excited in playing depending on the string being used. Moreover, frequency curves do not reflect the absolute sound level differences between violins in response to an identical excitation energy. A noticeably poor intrinsic loudness of violin UH may explain its deviance.

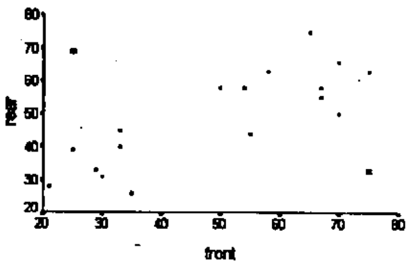

Figure 2. Preference (%) of each instrument in the rear vs. front audience

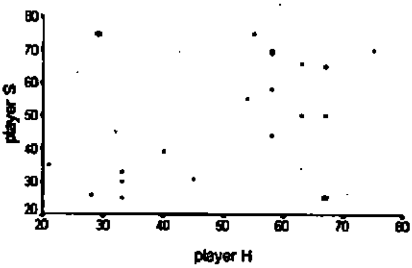

Figure 3. Preference (%) of each instrument played by S. and H. (professional players).

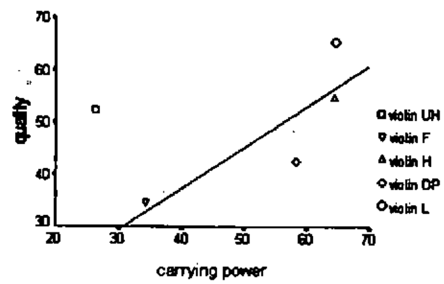

Figure 4. Ratings (%) of the attributes 'quality' and 'carrying power' of the 5 test violins (frequency curves see Figure 1). Values averaged over all items played. The values for violin UH were not used for calculation of regression.

Leaving this problem aside, we decided to design another test with only 3 violins which differed systematically in terms of the supposed contribution of the singer's formant and which had yielded a high correlation between quality and carrying power judgements in the first test: Violin L (highest ratings, amplitude of singer's formant more or less equal to other formant-like regions), violin DP (high ratings, amplitude of singer's formant considerably higher than the lower regions) and violin F (lower ratings, amplitude of singer's formant considerably lower than the amplitude of the region between 1 and 1.5 kHz). In an additional second set the players were asked to play as loud as they could in the presence of noise presented over loudspeaker in order to test that quality attributed to professional singers, namely the ability to make themselves heard in the presence of a loud orchestra.

RESULTS OF TEST 2

(6 January 1997, Cologne Philharmonic Hall).

The 3 violins selected for the test were played in pairs in all possible combinations. Between the actual test pairs, some other violin pairs were presented which did not take part systematically in the test. The same players S and H as in Test 1 again played the beginning of the Bruch Concerto. Listeners were again asked which of the violins in each pair they preferred in terms of quality and carrying power. In the second part of the test the same violins though in different sequence were played against the playback of a recording of an orchestra tutti. In a pre-test, the loudness of the playback had been set to a value which allowed a violin to be just audible (subjectively). The violinists were asked to play the bariolage part of the Prelude of the E-major partita (Bach).

In accordance with the results of Test 1 listeners' judgements on quality and carrying power were highly correlated. Taking the mean values of both attributes, the 3 violins show a clear ranking order with some disturbances depending on the way of playing (Figure 5): Violins L and DP constitute one group as opposed to violin F but with a clear predominance of violin L. In contrast to these findings the results of the second part of Test 2 show a very distinct predominance of violin DP over violin L (see Figure 6) which we attribute to the high energy of the singer's formant in the case of violin DP (see Figure 1)

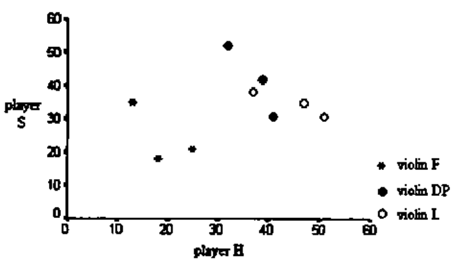

Figure 5. Combined judgements on quality and carrying power; correlation between both players.

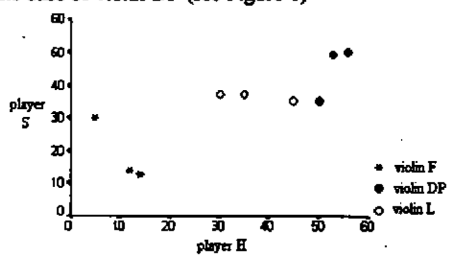

Figure 6. Judgements on audibility against noise.

Figure 7 suggests an additional explanation; it shows that violin DP was in fact louder, expecially in the frequency region above 2 kHz.

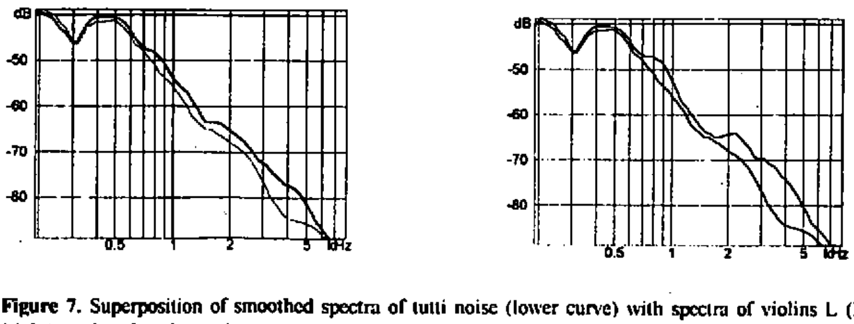

Figure 7. Superposition of smoothed spectra of tutti noise (lower curve) with spectra of violins L (left) and DP (right) as played against noise.

TEST 3

(12 March 1997, seminar room at the Institute of Phonetics, Cologne).

Recordings of the items of Test 2 (recorded at the position of the front audience group) were arranged on audio CD and played back in pairs over high quality loudspeakers. The audience consisted of students and staff members of the Institute of Phonetics.

Test 3 was designed to answer the following questions: Which is the relationship between the 3 selected violins F, DP and L and the other ones? What is the relationship between quality judgements based on recordings and those based on the live situation in Test 2?

No questions concerning the carrying power of the violins could be asked because of the play-back situation. Moreover, carrying power had been found to be no independent parameter in the previous tests. Thus the listeners were asked to mark that violin of a pair which was louder than the other one. Of course, recordings and playback were made with constant loudness levels in order to allow comparison.

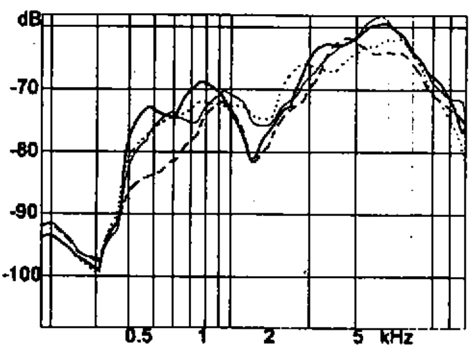

Figure 8. Smoothed FFT-spectra of the last 20 notes of the Bruch Concerto introduction: violin H (–), DP (—), F (...) and UH (- - -). Recordings were pre-processed by a high frequency emphasis of about 10 dB/octave.

In addition to the violins of Test 2 the violins H and UH (see Test 1) were used. Two more instruments (violin T, G. Testore, 1721, violin DD, new instrument by H. Dünnwald) were introduced to the test. Results show quite clear relations between the instruments and can be summed up briefly: In contrast to the live test situation in the Philharmonic Hall most instruments constituted one group with only small differences in quality judgements (50 - 55 %): L - H - UH - DP - DD. Violins T and F were rated lower than 40 %. Our findings indicate that quality differences between high standard instruments which listeners perceive in a live situation tend to be levelled out in play-back. As to the judgements of loudness a surprisingly clear ranking of the instruments appeared: violins H and DP were the best ('loudest') and violins F and UH the poorest. Figure 8 shows the result of an analytical experiment: The recordings of the violins made during Test 2 which also served as test stimuli in the play-back test were analysed by a FFT-algorithm; the number of points (sampling rate 44.1 kHz) could be adapted to the total duration of the music sample. In order to get a better reproduction of high frequency components the spectral analysis was preceded by a high frequency emphasis of about 10 dB/octave above 1 kHz. The smoothed spectra of the 4 violins show obvious differences of energy especially in the high frequency region between 2 and 4 kHz, but also in the region from about 0.5 to 1 kHz.

LISTENERS' JUDGEMENTS AND ACOUSTIC PROPERTIES OF VIOLINS

CONCLUSION

We tried to show that at least three comparable and principally independent features of violins exist: quality of sound, overall perceived loudness, and audibility against noise (orchestra tutti). On the basis of spectral analysis of the played test items in addition to measured frequency curves the following correlations with the features seem to be evident: Audibility against noise correlates with the absolute amplitude in the frequency region of the so-called singer's formant (~2-4 kHz) while subjective loudness seems to correlate with an additional relatively high amplitude in the lower formant region (< 1 kHz). Judgements on the tone quality of the test violins presumably correlate with a balanced relationship between both frequency regions and the absence of remarkable portions of energy in the middle frequency region (~1-2 kHz); this relationship, however, has not been sufficiently investigated yet. In our future work we will make use of manipulations of the spectral properties of violins and/or recordings in order to establish an adequate set of subjective attributes of violin sound in appropriate listening tests.

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