Rustle as an Attribute of Timbre of Stationary Violin Tones

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SUMMARY

During listening tests respondents were asked to describe in words the timbre of stationary violin tones of five different notes. A very high frequency of occurrence of the word 'rustle' ('šustivý' in Czech) was found for the highest tested D6 note. A significant positive correlation was found between frequencies of occurrence of the word 'rustle' and levels a) in third-octave bands below the fundamental frequency and b) higher harmonic components. The substantial influence of the spectral component below the fundamental on the perception of 'rustle' was verified by subsequent listening to the original and by filtering modified tones. The spectral component responsible for 'rustle' originated in the neighbourhood of violin body resonance modes A0, T1, and C3. The mean SPL of these spectral components is the only quantity able to distinguish tones with different magnitude of 'rustle'.

INTRODUCTION

Several approaches are used in the study of properties of violin sound, which are characterized from the point of view of 'resource' or 'direction'. Starting points for some of them can be the physical properties of violins, or more frequently, some of their parts. These approaches attempt to model mechanical procedures which can simulate properties of acoustical radiation of an instrument during the playing of tones, thereby influencing the resulting perception of instrument sound. Verification of such models most often consists of searching for the signature of modeled events in the spectrum of tones played by a musician, and rarely in discovering their perceptual consequences. A second starting point may be listening to different musical sounds, searching for a specific perceptual attribute and then attempting to explain it in terms of spectral or time properties of tones/signals. It is very difficult to discover its physical principle, and more difficult still to find a method for influencing its effect on the instrument. This second approach will be used in this article.

When we omit the unquestionable influence of the musician, the stationary violin tone is influenced by a series of factors: the resonant properties of the corpus, strings, bow, and bridge, and their mutual interaction. Tones can often differ in timbre when played on instruments that differ in quality. In particular, instruments of a lower quality with insufficient dynamic properties have various 'admixtures' and 'contamination' in the tone played. Yet a certain amount of admixtures, especially in attack transient, contribute to the character of instrument type and can help in its identification (Grey, 1977). Grey (1997) also identified low-amplitude, high-frequency energy in the initial attack transient, which is often inharmonically distributed, as the third perceptual dimension for the identification of different musical instruments. Jansson and Askenfelt (1997) deal with the identification of the C3 violin body resonance mode in the time flow of attack transient in violin tones, but did not refer to its perception. Terhardt (1974) quoted the conditions for perception of 'roughness': amplitude or frequency modulation of one harmonic, or the existence of two harmonics with slightly different amplitudes in one critical band. In both cases the reason for roughness are periodic events which can occur in the stationary part of the tone. However, it is possible to recognize some types of admixtures in violin tones which are not described as 'rough', which we have found in our study of timbre of stationary violin tones.

METHOD AND RESULTS

Spontaneous verbal description of timbre

The research on violin timbre was performed with tones of five notes: H3 played on the G string, F#4 on D, C5 on A, and G5 and D6 on E (Štěpánek et al., 1997 a), b), c)). Recordings were partly manipulated in order to reduce the influence of transient events on perception. The subjects listened to pairs of tones with headphones and compared the timbre of their stationary part. In one of the listening tests timbre was described with spontaneously spoken words. The results of these tests are also described in Štěpánek et al. (1999).

Word descriptions of timbre of eleven tones were obtained from ten subjects for each of the five notes studied. It was possible to assemble groups of relative words based on the results of correlation analysis of frequency of occurrence of words for individual tones. One of the groups of relative words (the significance level of the correlation was 0.1%) consisting of the words ***'rustle'*** ('šustivý' in Czech), ***'sandy', 'hissy', 'scrubs', 'dusty'*** and ***'horse hair'***, showed a prominent rise in overall frequency of occurrence in the highest tested D6 note (fundamental frequency 1175 Hz), which was comparable with the most frequently used words (FIGURE 1). Overall frequencies of occurrence of individual words from the group 'rustle' are in TABLE 1.

The following question arises: what are the physical attributes described by these words, whose meanings evoke contiguity with temporal envelope changes of the signal?

TABLE 1. Frequency of overall occurrences of spontaneous verbal descriptions from the group 'rustle' on individually tested notes.

Tone		H3	F#4	C5	G5	D6
Group 'rustle'		85	115	59	94	234
Rustle	Šustivý	48	51	24	44	101
Sandy	Pískový	15	24	12	14	53
Hissy	Syčí	-	16	-	13	26
Scrubs	Drhne	-	-	-	-	22
Dusty	Zaprášený	22	24	23	23	16
Horse hair	Žíně	-	-	-	-	16

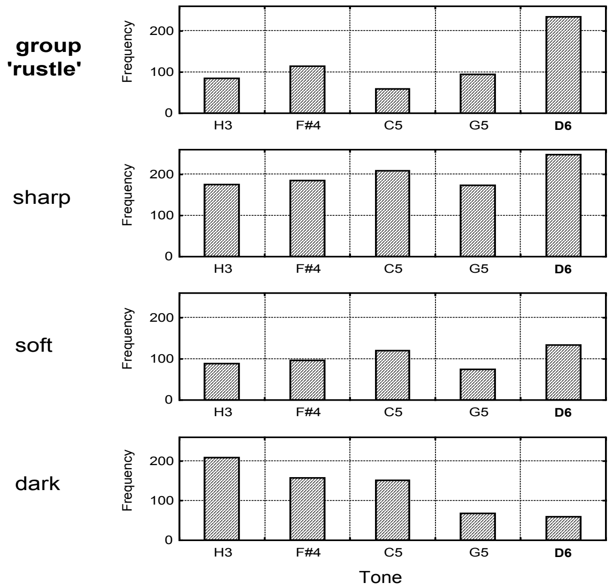

FIGURE 1. Frequency of overall occurrence of spontaneous verbal descriptions from the group 'rustle' compared with that of very frequently used words.

Correlation analysis of verbal descriptions and physical characteristics

The search of physical attributes of tones studied was based on spectral and time analyses of signals carried out using MATLAB (- Matlab, 1996).

Sound Pressure Levels (SPL) in third-octave bands and in individual harmonics were determined from time-average power spectra calculated using Welch's method for power spectral density estimation from quasi-stationary parts of the signals (8192 samples window, Hanning window filtering, 4096 samples overlap).

The frequencies of occurrence of words from the group 'rustle' were correlated with levels in third-octave bands and with levels of harmonics. Significant correlations (TABLE 2) showed that the reason for the occurence 'rustle' may be the presence of high levels in the two broad frequency bands: either below the fundamental (from 200 to 900 Hz) or above 8000 Hz (higher harmonics starting from the seventh), see FIGURE 2.

TABLE 2. Significant correlations between verbal descriptions from the group 'rustle' and third-octave band levels or levels of harmonics. The values of the Pearson correlation coefficient and significance levels in % are included.

Word	**Third-octave [Hz]**						
	250	**315**	**400**	**500**	**630**	**800**	**2000**
Group 'rustle'	0.89 0.1	0.78 1	0.81 1	0.89 0.1	0.77 1	0.80 1	0.71 5
Rustle	0.89 0.1	0.82 1	0.77 1	0.89 0.1	0.82 1	0.81 1	0.70 5
Sandy	0.78 1	0.67 5	0.71 5	0.69 5	0.62 5	0.60 5	0.72 5
Hissy	0.67 5	0.53 10	0.72 5	0.66 5	0.56 10	0.57 10	0.66 5
Scrubs	0.73 1	0.59 10	0.77 1	0.87 0.1	0.68 5	0.92 0.1	0.42 -
Dusty	0.83 1	0.77 1	0.68 5	0.93 0.1	0.56 10	0.70 5	0.72 5
Horse hair	0.88 0.1	0.82 1	0.74 1	0.90 0.1	0.75 1	0.82 1	0.55 10

Word	**Harmonic No.**							
	7	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Group 'rustle'	0.77 1	0.61 5	0.72 5	0.85 0.1	0.79 1	0.86 0.1	0.59 10	0.65 5
Rustle	0.77 1	0.60 5	0.72 5	0.85 0.1	0.84 1	0.88 0.1	0.52 10	0.59 10
Sandy	0.65 5	0.53 10	0.61 5	0.73 1	0.65 5	0.77 1	0.73 1	0.76 1
Hissy	0.77 1	0.54 10	0.58 10	0.78 1	0.59 10	0.64 5	0.63 5	0.81 1
Scrubs	0.68 5	0.56 10	0.59 10	0.67 5	0.71 5	0.64 5	0.13 -	0.30 -
Dusty	0.69 5	0.52 10	0.63 5	0.88 0.1	0.68 5	0.73 1	0.67 5	0.48 -
Horse hair	0.63 5	0.55 10	0.81 1	0.74 1	0.74 1	0.88 0.1	0.39 -	0.34 -

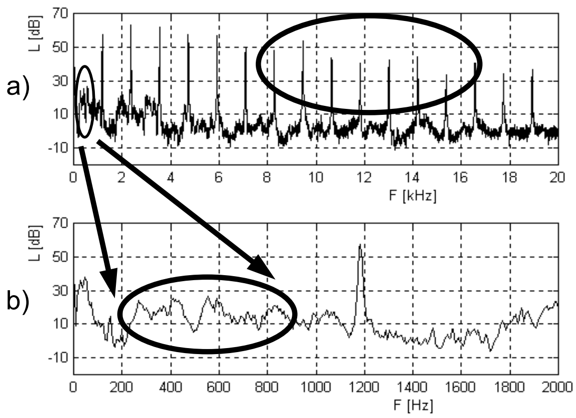

FIGURE 2. The power spectrum (a) and its lower part (b) of the D6 note; regions of third-octaves and harmonics, whose levels have a significant correlation with frequencies of occurrence of words from the group 'rustle', are marked with ellipses.

Complementary listening tests

In identifying the true physical attribute responsible for the subjects' selection of the term 'rustle', ***complementary listening tests*** of some tones of D6 note were carried out. Five from an original set of eleven tones were selected for these tests: one with a low, two with a medium, and two with a high frequency of overall occurrence of words from the group 'rustle' (numbered as 1, 2 and 3, 4 and 5, respectively).

Preparation of stimuli for the tests consisted of ***filtering original signals***, which required sufficient suppression of levels in the band above 8000 Hz (lowpass filtering) or in the band 200 - 900 Hz (bandstop filtering), or in both bands simultaneously. Moreover, neither amplitudes nor temporal flow in the rest of the signal could be changed. These requirements are met by the Chebyshev type II filter which has no passband ripple. Examples of spectra of original and filtered signals are in FIGURE 3 and 4 together with the filter parameters used. The filters were cascaded together for filtering in both bands.

The first complementary test was the pair test of ***dissimilarities in timbre*** performed separately with each original signal with modifications obtained through lowpass, passband and cascaded filtering.

In the second complementary test—the ***verbal attribute magnitude estimation*** (VAME) test—all chosen signals and their filtered modifications were included at a single time, and the subjects rated the magnitude of the verbal attribute 'rustle' for all signals listened to individually.

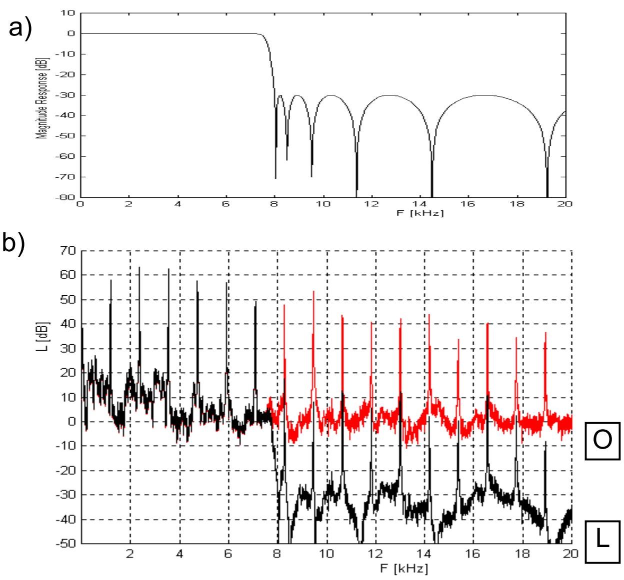

FIGURE 3. Chebyshev type II lowpass filter (a), parameters: order n = 12, passband corner frequency Wp = 7.5 kHz, bandstop corner frequency Ws = 8 kHz, bandstop attenuation Rs = 30 dB; time-average power spectrum (b) of the original (O), and the lowpass filtered (L) signal.

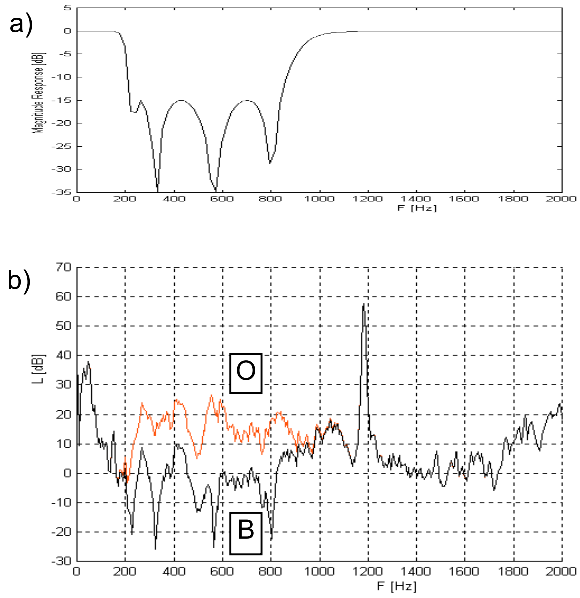

FIGURE 4. Chebyshev type II bandstop filter (a), parameters: order n = 4, passband corner frequencies $Wp_{1,2}$ = [170, 1000] Hz, bandstop corner frequencies $Ws_{1,2}$ = [230, 800] Hz, bandstop attenuation Rs = 15 dB; detail of time-average power spectrum (b) of the original (O), and the bandstop filtered (B) signal.

In both tests a range from 0 (no dissimilarity or no magnitude of verbal attribute) up to 5 (maximum dissimilarity or maximum magnitude of verbal attribute) was used, and half points were allowed. Given the small number of stimuli and listeners (6 listeners in each test) it is possible only to diagram the results.

From the results of the dissimilarity tests (FIGURE 5) it is apparent that the ***timbre changed more with the suppression of components below the fundamental*** (B filtering) than of higher harmonics (L filtering). This is due to the presence of dissimilarity equations d(OB) > d(OL) and d(BC) < d(LC) in four out of five signals.

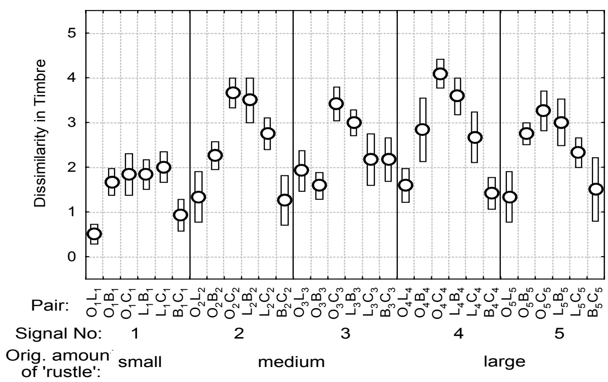

FIGURE 5. Dissimilarity test results for selected signals. The circle demonstrates subject-averaged timbre dissimilarity in signal pairs; bars indicate standard error. Signal labels: O = Original, L = Lowpass, B = Bandstop, C = Cascade filtered (C=L&B); the index indicates signal number.

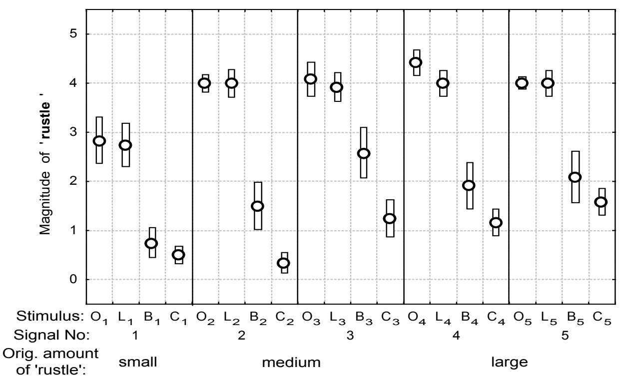

FIGURE 6. Verbal attribute magnitude estimation (VAME) test results for signal set originated from all signals. The circle demonstrates subject-averaged magnitude of 'rustle'; bars indicate standard error. Signal labels: O = Original, L = Lowpass, B = Bandstop, C = Cascade filtered (C=L&B); the index indicates signal number.

Based on the VAME test it is possible to conclude that the ***magnitude of 'rustle' decreased only in signals with the suppression of components below the fundamental*** (FIGURE 6). This is due to presence of magnitude equations $\{m(B), m(C)\} < \{m(O), m(L)\}$.

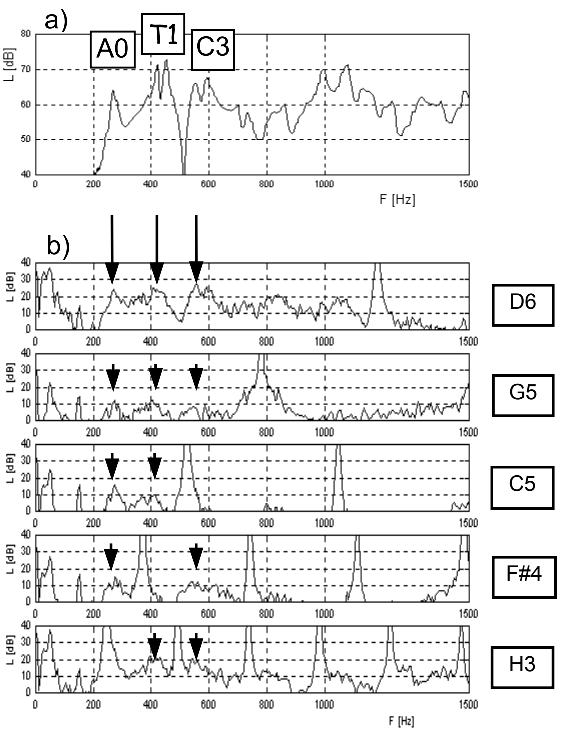

FIGURE 7. Comparison of the violin frequency characteristic (a) with time-averaged spectra of quasi-stationary tone parts (b) for the violin with high degree of 'rustle' (instrument number 4). Spectral signatures of violin modes A0, T1 and C3 in spectra are marked with arrows.

Detection of the source for 'rustle'

The detection of the source of acoustic radiation of violins below the fundamental was made by comparing the spectra of tested signals and the corresponding frequency characteristics of the instruments. Measurement of the frequency characteristic was performed using Dünnwald's method (Dünnwald, 1984). As the levels in the third-octave band with a center of 800 Hz in signals studied are typically lower by 5 to 10 dB than in other bands below the fundamental, we have concluded that the phenomenon ***'rustle' in violin tones is induced by the radiation in the neighbourhood of resonance modes A0, T1, and C3*** which usually lie in the regions from 260 to 290 Hz, from 400 to 500 Hz, and from 500 to 600 Hz, respectively (the modes are designated according to Moral and Jansson, 1982). It is possible to recognize the spectral signature of these modes in all five spectra of notes studied, but their levels are highest in the D6 note (FIGURE 7).

Nature of 'rustle' signature in the spectrum of violin tone

Five signals used in complementary tests were submitted for additional analyses. With respect to the frequency position of modes A0, T1, and C3, determined from the frequency response of the five violins studied, the region below the fundamental responsible for 'rustle' was divided into three frequency bands: 230-330 Hz (band A), 330-480 Hz (T), and 480-650 Hz (C). Amplitude spectra were calculated from quasi-stationary parts of the signals using the Short Time Fourier Transform (STFT) method with 23.2 ms time intervals and 11.6 ms time step. However these parameter values have not influenced the results of the signal comparison. A spectrogram of the quasi-stationary part of the signal with a frequency discrimination of 5.4 Hz was obtained by the frequency ZOOM (FIGURE 8). This spectrogram illustrates previously defined division of the frequency region below the fundamental into bands in the neighbourhood of violin resonant modes.

SPL were calculated in A, T, and C frequency bands from the STFT amplitude spectra. Time-flows of levels obtained in these bands in all five signals were statistically evaluated, revealing that time-flow level sequences in individual bands are aperiodic, random, and have negligible trends. All of these sequences are mutually uncorrelated. Standard deviations are comparable in all time-flow level sequences.

Most frequently dominant levels are in the band of resonant mode T1 (FIGURE 9), the histogram of distribution of levels in this band (FIGURE 10) indicating that not even the distribution of levels can distinguish signals with different magnitudes of 'rustle'. Thus, the only determined quantity able to distinguish individual signals with different magnitudes of 'rustle' in the region below the fundamental remains the mean value of time-flow level in bands A, T, and C (FIGURE 9). This mean is closely connected with the levels in third-octave bands below the fundamental which have significant correlations with degree of 'rustle'.

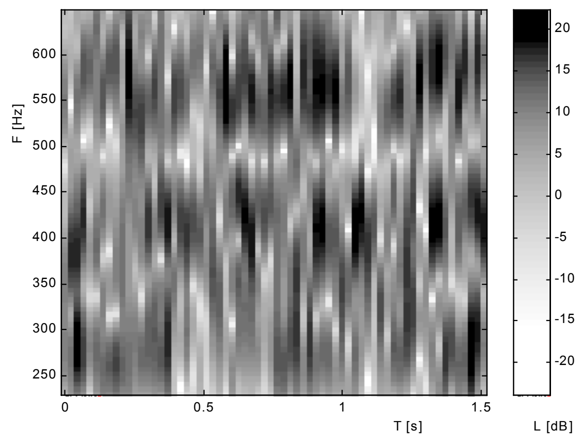

FIGURE 8. Spectrogram of frequency band from 230 to 650 Hz made from the quasi-stationary signal part of the D6 tone with a high degree of 'rustle' (instrument number 4).

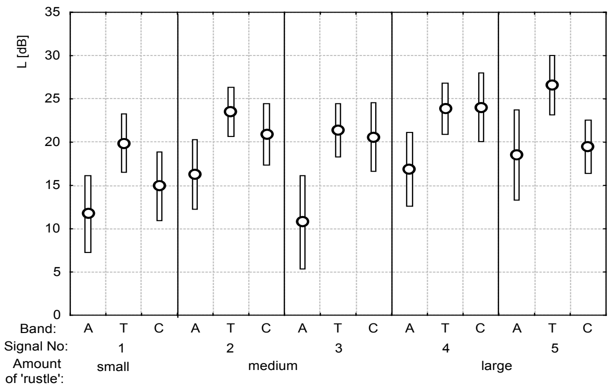

FIGURE 9. Mean values (circles) and standard deviations (bars) of time-flow of SPL levels for signals studied in frequency bands 230-330 Hz (A), 330-480 Hz (T) and 480-650 Hz (C).

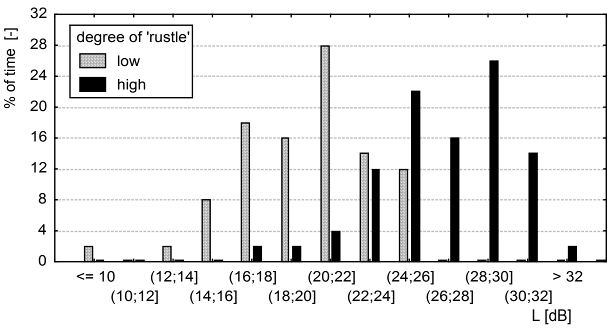

FIGURE 10. Histogram of the distribution of levels in time-flow for the frequency band 330-480 Hz and signals with a low and high degree of 'rustle'.

DISCUSSION

During the search for the physical attributes of 'rustle' an interesting fact from the methodological point of view emerged: the coincidental occurrence of several events, all of which correlated with the same aspect of perception. Only a complementary listening test could determine which of them is substantial for perception. Generally speaking, while it may be insufficient to discover some physical correlate in order to explain the perceptual event, it is essential to verify the influence of the found attribute on perception.

Complementary listening tests clearly demonstrated that the timbre attribute named by subjects as 'rustle' is caused in the studied context (quasi-stationary violin tones of the D6 note with manipulated transients listened to monophonically with headphones) predominantly by the presence of components below the fundamental in the range from 200 to 900 Hz.

The magnitude of 'rustle' decreased substantially but did not disappear with the filtering of components below the fundamental (FIGURE 6). It implies that in addition to these components, other spectral components which vary in time could participate on the perception of 'rustle' but to a minor degree, and which become salient when the more prominent components below the fundamental are removed. A possible reason can lie in temporal changes of level of a harmonic or of higher interharmonic levels. Thus, the source of 'rustle' in these frequency regions as well as in lower violin tones requires examination.

A more detailed study of the properties of tested signals showed that the reason for the perception of 'rustle' in the D6 note are time fluctuations of levels of the spectral components in the neighbourhood of resonant modes A0 (air cavity mode), T1 (top plate mode), and C3 (corpus or body mode). The nature of the fluctuations is the same for all frequency regions and tested signals mentioned; the condition for the perception of, or even for disturbance by 'rustle' is given by the mean value of the level in stated frequency bands. From FIGURE 10 it is recognizable that the threshold level for the saliency of 'rustle' in perceiving of our tones is approximately 25 dB. This threshold was also corroborated in the most 'rustly' signal on G5 note.

The principle for sound production from the violin is oscillation of a string excited by the bow, transformation of the motion of the vibrating string through the bridge to the resonator - the violin body, which radiates the largest part of the sound energy. Hence, the source of sound energy is the bowed string, the violin body acting only as an additional frequency filter. This implies that some aperiodic events in string motion are responsible for radiation from the body which is randomly distributed in time and level in the frequency region from 200 to 900 Hz.

McIntyre et al. (1981) listed three types of aperiodicities in bowed string motion. The first is radiation of energy on subharmonic frequencies determined by the position of the bow on the string, or more precisely, by the division of the string by the bow into two parts.

The active width of the bow by playing our tested tones *mezzoforte* was approximately 0.4 - 0.5 cm. The length of the E string for the D6 note is from 17.5 to 18.0 cm. By playing D6 notes *naturale* the bow distance from the bridge was approximately 2.3 cm, it is approximately one seventh or one eighth of the active string length. Corresponding subharmonic frequencies are 168 Hz or 147 Hz, which lie out of the 'rustle' producing frequency region 200 - 900 Hz. These values for subharmonic frequencies are indirectly supported with the N4 spectral notch position for the D6 violin note on the seventh or eighth harmonic in a spectrum observed for the same signals (Štěpánek at al., 1997 a)).

A possible reason for 'rustle' remains other sources of aperiodicity - flyback jitters and spikes (McIntyre et al., 1981), both of which are randomly distributed in time. Their occurrence gives rise to broadband noise from which the violin body radiates more energy on the frequencies corresponding to resonant modes.

Frequency of occurrence of the word 'rustle' had a significant and negative correlation with perceived overall quality in original tests of timbre. A significant rise of levels of components below the fundamental on high violin tones is apparently connected with dynamic properties of lower-quality instruments.

ACKNOWLEDGMENTS

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