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MICROSTRUCTURE OF SOUND: FORMANTS IN THE DYNAMICAL SPECTRA OF VIOLIN SOUNDS

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The aim of the present study was to obtain the picture of the structural changes occuring in the spectra of a violin sound, with the four bowing techniques: detaché, staccato, legato and martele. FFT analysis has been carried out using the system Volyzer [19] and Split [13] on IBM XT personal computer. Experimental material selected for this investigation consisted of the isolated sounds g (196 Hz), d^1 (293.7 Hz), a^1 (440 Hz), e^2 (659.3 Hz) and d^3 (1175 Hz) obtained with five instruments. Total number of randomly selected dynamical spectra, was 35. The tone structures have been analysed within 0–220 ms timescale, in 20 ms segments. In this time span the spectrum continually undergoes the changes comprising the range of the spectrum, the number of the formant maxima and their amplitude levels. Three types of formants exist: continuous, non-continuous and fragmentary. The changes of the position of the formant maxima on the frequency scale, the forms in which the amplitude levels of these maxima vary, the durations of the specific formant creation and the stabilization of the full formant set in the spectrum of sound have been analysed.

1. Introduction

In vast literature devoted to the acoustic problems of a violin sound, the natural frequency patterns of vibrating plates relating to so-called material resonances and airborne resonances of the instruments (refered to as "Helmholtz's air resonances") are those most widely dealt with [18]. Despite of the rich experimental material and broad discussions, both problems still remain open [17]. The natural frequencies of the instrument affect its frequency characteristics. The frequency response functions are either obtained from direct monitoring of the amplitude of vibrations at the locations of interest of the instrument (corpus or the bridge) or recording the amplitude of the acoustic signals resulting from these vibrations. In the analysis of resonant structures of frequency response functions when seeking the vocal attributes of an instrument, one may use the term "formant responses" [1]. The term "formant" can also be defined as the maximum on the envelope of the sounds spectrum.

The particular sounds of stringed instruments can be characterized by their detailed structure, also called the microstructure, consisting in the changes of frequency, intensity and spectral structure [16]. Performance of the violin music features a wealth of these intrinsic sound changes [8], [9]. Among other things, it relates to the possibility of applying different bowing techniques. It has been found, in the course of preliminary studies, that the formant patterns in the dynamical spectra of bow generated natural sounds of a violin, as well as the frequency, undergo changes as a function of time [5]. These changes concern the position and amplitude of the formant's maxima. The shifts on the frequency scale of the formant's maxima do not posses a single tone local change character (as exemplified by the study made by B.M. MOORE [15]), but occur in whole ensemble of the partials of a given sound [17]. There are various causes for it. Among other factors, these changes may result from the change of a system of forces, acting on an instrument during different forms of the bow and string interaction [11], [12].

The purpose of the present study is to obtain an analytical picture of structural changes occuring in the process of formation of a dynamical spectrum of natural, isolated sounds of a violin using various bowing techniques, especially including formants patterns.

2. Scope and methods used in the study

Fundamental goal of the investigations described in this paper was to examine a possibility to select the most characteristic structural features of the bowing techniques like: detaché, legato, staccato and martele, using the methods of analysis of the profile of dynamical spectra of a violin sounds.

The specific tasks are as following:

— to determine the changes occuring in the formant pattern during the time of formation of an violin sound,

— to determine the change in amplitude levels of the formant maximum in the sound spectrum in this time,

— to analyse a stabilization process of the formant's pattern.

a. *Experimental*

Five instruments have been selected for the investigation, including two antique, but regularly in use violins, namely, B. DANKWART'S (17 century violin), (Da) and the violin (Am) from N. AMATI'S shop (16/17 century), two violins from contemporary artists violin-makers (these two instruments, further refered to as Ca and Vi, had been awarded the high prizes at VII th International Wieniawski Competition of Violin-Makers in Poznań, in 1986) and an experimental violin (Ka), whose back plate was finished in a non-standard way.

The instruments were played by a professional musicians with academic degree. The four bowing techniques were used in exciting the isolated sounds in the performed tests consisting g, d^1, a^1, e^2 and d^3 sounds.

Following points have been ascertained with the aim to standarize the conditions of the performance:

— all the recordings took place in the same location with precisely determined configuration of the player and the microphone,

— the violinist repeatedly performed the test sounds on all five instruments in the same test configuration,

— playing vibrato was avoided,

— the violinist was provided an opportunity of a rehearsal of the tests using all five instruments,

— in order to adjust to the modified requirements of the test, regarding a duration of signals and their intensity level, the player was making preliminary performances,

— always the same bow and rosin was used.

With regard to the fact, that every natural sound signal of stringed instruments is an individual and irreproducible phenomenon, the performer of the tests was only provided with general instructions necessary to minimize the differentiation of intensity levels and durations of the produced sounds. He had a freedom of performing the particular tests as to obtain best tone of an instrument when playing *"mf"*. Detailed measurement of the intensity level and time during the test, was abandoned. There is no opportunity though, to impose unified criteria for all the signals under study, since they are bound to be of a different character, due to the accepted choice of the different techniques of playing a violin.

The purpose of applying the detaché and legato technique is to obtain quasi-stationary signals, while staccato and martele produces impulse-like-signals. The violinist took a fixed position with reference to the microphone by stepping on a marked place on the floor. The microphone was mounted opposite the bridge in the distance 30 to 35 cm. The amplitude level of the generated signal was monitored before each group of tests, to enable the performer to adjust the dynamics to within 75 to 80 dB range and to adjust the duration of the signal. The violinist was timing the play in such a way, as to obtain one pluck of bow per second with the detaché technique, one sound per second in legato, two with martele and four with staccato techniques.

Recordings have been made in M. Groblicz concert hall in the Museum of Musical Instruments in Poznań the same in which violin instruments were rehearsed at the all International H. Wieniawski Competitions of Violin Makers, as well as the acoustic tests associated with the H. Wieniawski Competitions [5].

The sounds were recorded with tape recorder model MP 223. Best recordings were chosen for the detailed analysis, of which 35 were randomly selected, with due representation of all four performing techniques.

b. Spectral analysis

Spectral analysis was conducted with fully computerized method using an PC IBM XT. Two programs: a modified SPLIT-Signal Analysis Program [13], [14] and System VOLYZER [19], have been used. Sampling rate amounted to 50000 samples per second (kS/s), filter cut-off frequency was 25 kHz at the attenuation 80 dB/octave. Signal segmentation time was 20 ms. The dynamics of the spectra was studied within 0 to 220 ms time interval (Fig. 1). The choice of such an interval was made on the basis of the published data [3], [17] and the results of the authors own preliminary analyses where it is believed that the adopted time-span should encompass the sound formation period (attack) and beginning of the steady state (see Fig. 1). The coding of individual signals is shown in Table 1.

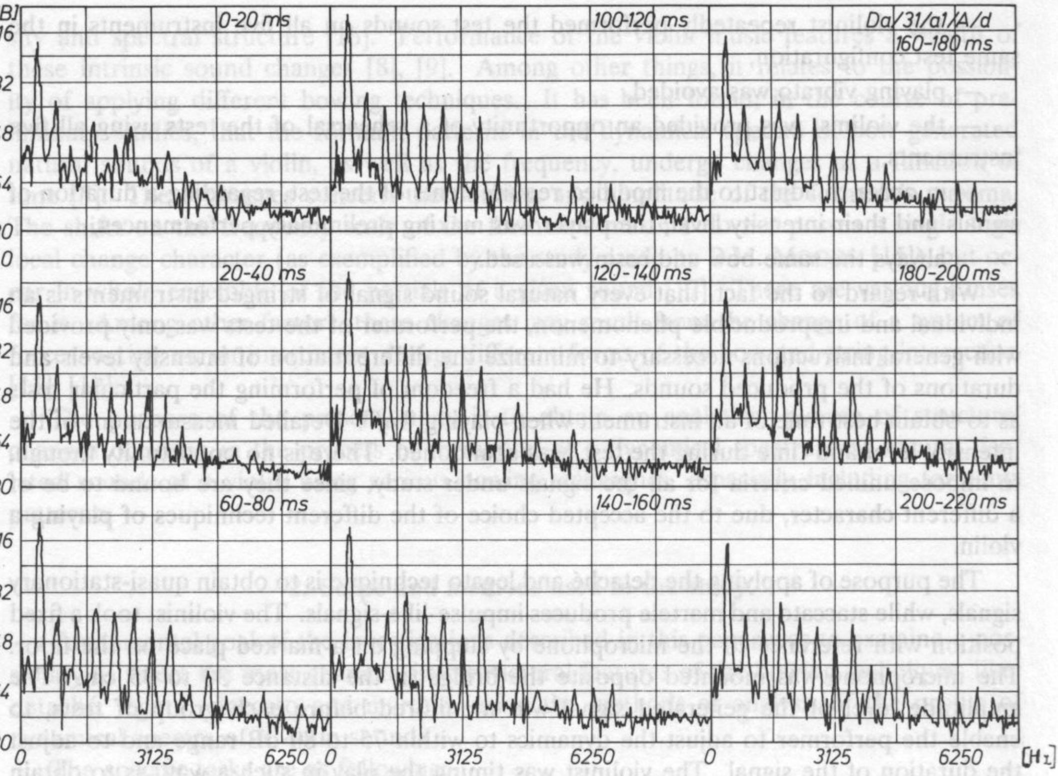

FIG. 1. Time-evolution of the dynamic spectrum of Da31 a^1/A detaché sound.

Table 1. Coding system of the sounds data

1	Da,Ka,Am,Ca,Vi
2	od 1 do 35
3	g, d^1, a^1, e^2, d^3
4	G,D,A,E
5	s,m,l,d

1. Instruments symbol.
2. Sounds number.
3. Sounds frequency: g [196 Hz], d^1 [297.3 Hz], a^1 [440 Hz], e^2 [659.3 Hz], d^3 [1175 Hz]
4. String.
5. Techniques: s — staccato, m — martele, l — legato, d — detaché.

3. Processing and the analysis of the results

The sound material for the analysis are collected in Table 2.

Table 2. List of the sounds selected for the analysis

Sound	Instrument	Techniques: detaché	legato	staccato	martele
g	Da	g/G – (29)	—	—	—
	Ca	g/G – (30)	—	—	—
	Ka	g/G – (2)	—	g/G – (5)	—
d^1	Da	—	d^1/D – (10)	—	—
a^1	Da	a^1/A – (17)	a^1/A – (11)	a^1/A – (14)	a^1/A – (8)
		a^1/A – (31)	a^1/A – (16)	a^1/A – (19)	a^1/A – (9)
		a^1/G – (15)	—	—	a^1/A – (35)
		a^1/D – (18)	—	—	—
	Ca	a^1/A – (32)	—	—	—
	Ka	a^1/D – (4)	a^1/A – (28)	a^1/A – (3)	a^1/A – (7)
	Am	a^1/A – (22)	a^1/A – (23)	a^1/A – (21)	a^1/A – (26)
	Vi	a^1/A – (33)	—	—	—
e^2	Da	—	e^2/D – (12)	—	—
	Ca	e^2/E – (34)	—	—	—
	Ka	e^2/E – (6)	e^2/D – (1)	—	—
	Am	—	—	e^2/E – (24)	e^2/E – (25)
d^3	Da	—	—	—	d^3/E – (13)
	Am	d^3/E – (27)	—	d^3/E – (20)	—

Every dynamical spectrum of a sound was undergoing an individual careful analysis. Frequency range of the partial tones in a spectrum and its variability within the separate sounds during the signal persistance, was measured, aimed at obtaining an exact characteristics of the analysed sounds. It has been accepted, that this range is defined by the highest harmonic recorded at least 4 dB above noise level.

Following structural features have been examined in the analysis of the fine structure of a sound:

— distribution of the formants on frequency scale,

— changes of the amplitudes of formants maxima in the duration time of signal,

— time in which the complete formant structure developes.

Formant maximum was identified as the maximum of an amplitude envelope only, if the discrete component tone at which the maximum was localized, exceeded by at least 3 dB, amplitude levels of the adjacent minima on this envelope. Such a predominance creates conditions to effect an acoustic impression by a formant [6], [7].

a. The range of tone components in a spectrum

The range of tone components occuring in the spectra of different sounds of a violin is largely diversified. In spite of the standarization of experiments i.e. the conditions of a sound generation and recording, the sounds of the same pitch, excited with different instruments or with different strings as well as those produced by diverse techniques may, vary with regard to their harmonics contents.

Table 3. Changes of the range of the partials n in a dynamical spectrum of a^1 sound of a violin with reference to the initial state n_1

Tech-nique	In-stru-ment	n_1	$\Delta n = n_k - n_1$									
			Segmentation Time [ms]									
		0–20	20–40	40–60	60–80	80–100	100–120	120–140	140–160	160–180	180–200	200–220
m	7	15	0	−3	9	9	10	18	16	16	18	18
	8	18	0	−3	−4	−4	−4	−4	−4	−4	−4	−4
	9	10	0	2	1	2	1	1	1	0	0	0
	26	15	3	4	3	3	3	3	3	3	—	—
	35	13	0	8	10	8	12	4	8	8	7	13
l	28	14	−5	0	−1	−4	−1	0	−1	−4	−4	2
	16	15	0	0	0	−1	0	1	1	1	1	1
	11	9	2	11	6	5	5	5	5	8	8	7
	23	13	0	3	11	3	1	2	3	7	4	1
s	3	9	6	7	12	13	13	13	8	7	—	—
	14	15	0	−4	−5	−5	−5	−5	−5	−6	−7	−7
	19	20	−3	−4	−4	−6	−6	−10	−10	—	—	—
	21	13	1	0	0	0	1	0	−1	−2	−3	−4
d	4	12	0	−2	1	2	−1	0	0	−1	−1	−2
	17	10	2	3	0	1	1	0	1	1	0	1
	31	12	0	0	3	3	3	2	1	3	3	4
	32	13	10	6	3	3	3	11	12	11	13	5
	33	8	0	0	2	1	0	0	1	0	0	1
	15	7	0	8	9	1	4	4	3	1	3	5
	18	11	−2	−4	−2	−3	−3	−2	−2	−3	−3	−2
	22	5	3	6	6	8	6	6	6	7	8	7

In Table 3 the results are collected of the analysis of the range changes for a^1 sounds grouped according to various techniques excitation. In the column "n_1" a number is given of the tone components limiting spectral range obtained at the onset of a tone (0–20 ms). In the following columns, the changes of this number, recorded in the process of the spectrum development and calculated with reference to the value of n_1, are given. The results are indicative of the fact, that the changes occur in all these sounds and adopt various forms. In many instances these are oscillational changes. Using staccato technique, for one of these sounds the spectral range was observed to increase up to a certain maximum value and was subsequently, systematically decreasing, with two other sounds the maximum range occured at the beginning of the spectrum, then also diminished. In the fourth sound, a stable pattern was maintained for the first 140 ms, later the range maximum was reduced. In the presented group of 21 spectra, in five cases the oscillations did not exceed 3 dB, which can be understood as a quasi-stabilization For 10 sounds these oscillations were larger. When using martele, detaché and legato techniques, the range and the forms of these changes were diversified; the least changes took place in case of legato. With only 3 spectra, a maximum of the range was recorded at the moment of impact of the bow on the string.

Various factors, like for example, the forces pattern resulting at the contact point of strings and a bow (this factor frequently quoted) [11], [12]. There is no doubt that the design of instruments and material properties are of great importance [2], [10]. Evidently, apart from oscillations of the frequency [8], [9], the oscillation of the maximum range of a spectrum often occur as a micro-structural feature of the violin sound.

b. Time and frequency distribution of formant maxima

Detailed analysis of the dynamic spectra, conducted with regard to the process of time development of the formant pattern within a sound, allows to distinguish three kinds of the formants: those distinctly stable which persist continuously, with perhaps only a single break during the whole sound duration (Rs), those nearly continuous (with three very short pauses, at most) (Rn) and the formants arising instantaneously at various frequencies (Rf). The latter should be referred to as "flickering".

In Figs. 2, 3 and 4, these three different sets of formants are exemplified. The first shows the formants of a^1/A sound of various instruments (Fig. 2), the second set refers to a^1/A sound of Dankwart's violin excited with varying bowing techniques (Fig. 3) and the third — the sounds a^1 and e^2 excited with legato technique (Fig. 4). The solid line connect formant's maxima of the stable and the discontinuous formants, occurring in the relevant timescale. In a few sounds, particularly in case of the techniques martele and legato, deviations of the formants frequencies within the range of two neighbouring harmonics, take place. It may result from a modification, during the sound generation, of the system of forces exciting oscillations in the sound box of the instrument (repositioning of the bow on the strings, for instance). Then, various parts of the resonant plates, of different eigen-frequencies, become active. Their patterns depend on several factors, including resonant wood structure and the shaping of an instrument. Numerous response functions have been published by several authors, which evidence the possibilities of these factors to have an effect on the generated sound [4]. The formant patterns in the spectra of various instruments, are remarkably different. In all a^1/A sound the lowest formant is present continuously. The "flickering" formants preferably occur at the higher frequencies of the particular sounds. They arise in great number when detaché or staccato techniques are used (more than 17, in g and a^1 sounds spectral). These observations are illustrated in Fig. 5, comprising all the results of the analysis, of the whole set of the investigated sounds spectra. This figure plots the maximum numbers of the formants presented during a sound time-history, are grouped according to the bowing technique used in the experiment (Fig. 5). In the two groups of stable and discontinuous formants, the latter represented 19% within the staccato technique group, 17% — detaché, 14% — martele, whereas in the legato group, the discontinuous formants represented only 9%. In Fig. 6 the maximum numbers of formants in the spectra of particular sounds are given as a function of the maximum ranges of these spectra.

General trend of the dependence of the formants on the number of partial tones is clearly drawn. The correlation coefficient calculated with Spearman's ranking method is 0.79, which points to a high correlation between the spectral range and the number of formants. It results, to some extent, from the fact, that the number of partials is always of limited influence on the number of formants. For example, only three formants may arise within six partials pattern. From the dispersion of the results, it becomes evident that the number of harmonics is not the only factor decisive on the number of formants.

In Fig. 7, the overall range of the number of formants is presented together with the respective spectral ranges, obtained in the durations of a^1/A sound, with different bowing

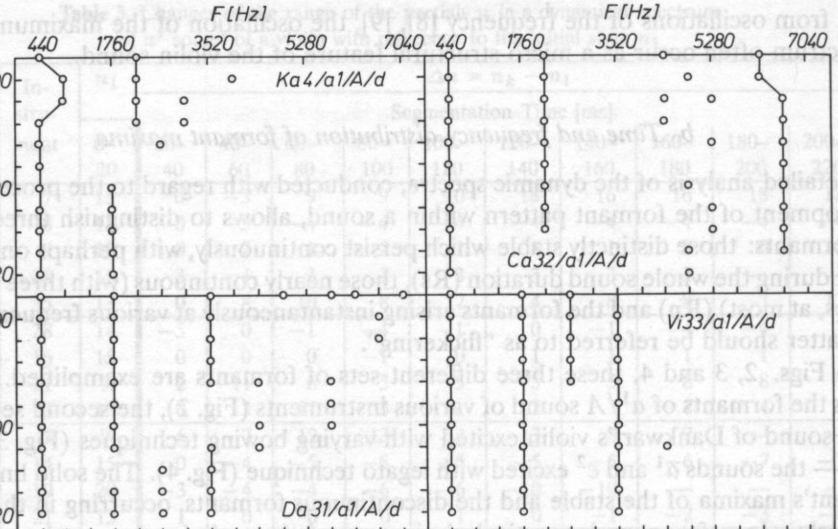

FIG. 2. Distribution of formant maxima in a^1/A sound spectra of various instruments (t — segmentation time, NO — number of a harmonic, F — frequency).

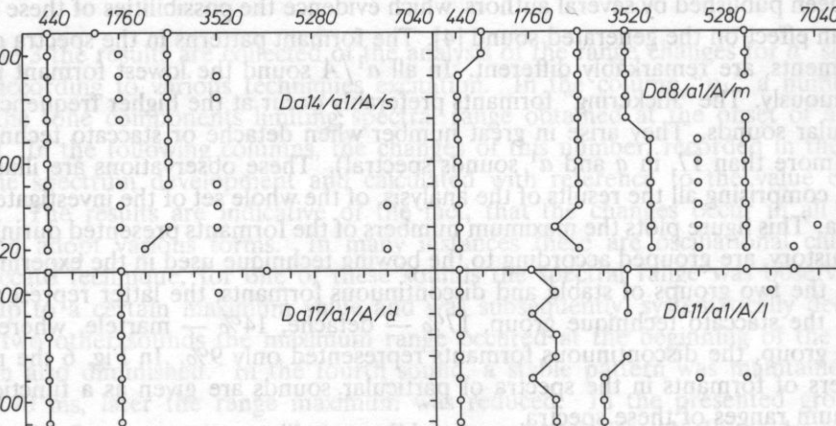

FIG. 3. Distribution of formant maxima of a violin sound a^1/A Da at different bowing techniques (t — segmentation time, NO — number of a harmonic, F — frequency).

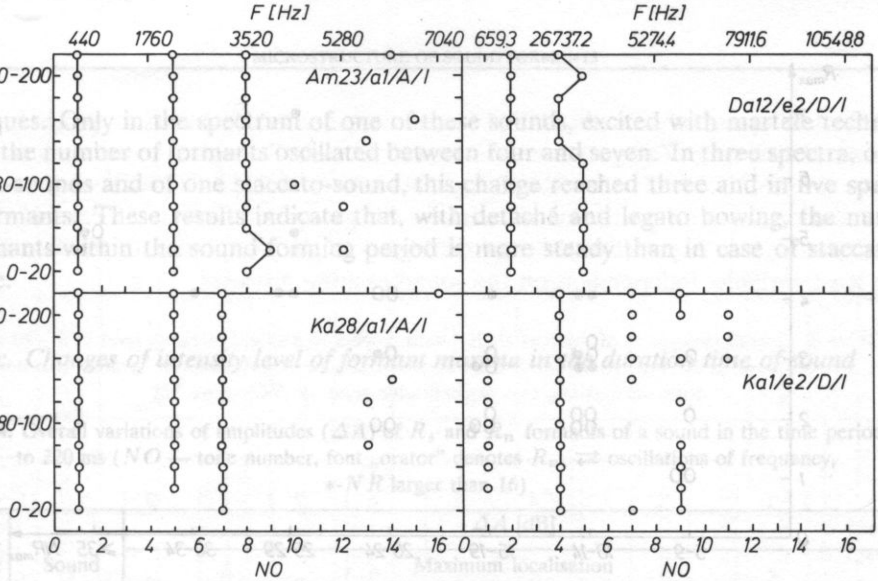

FIG. 4. Distribution of formant maxima of legato generated sounds (t — segmentation time, NO — number of a harmonic, F — frequency).

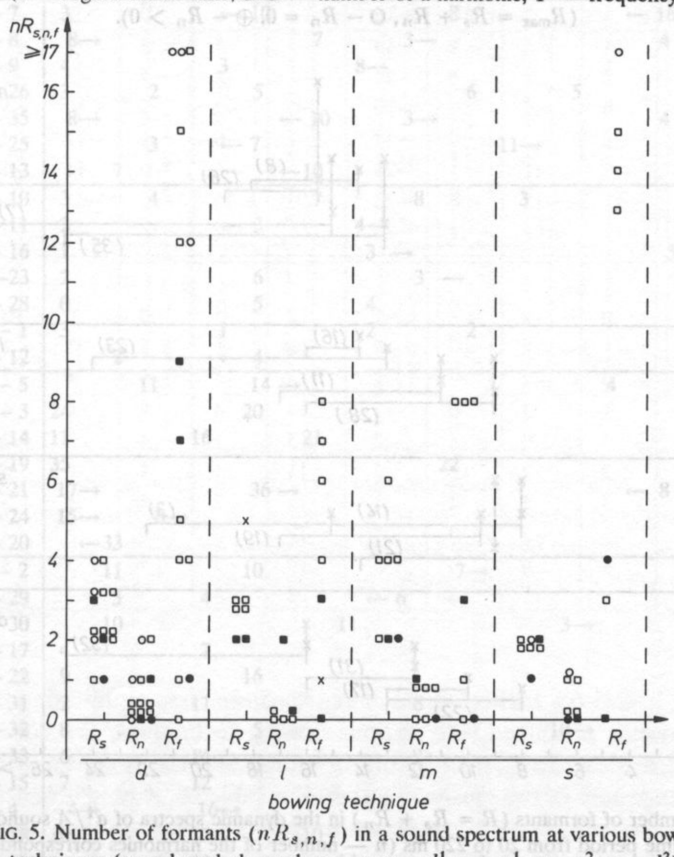

FIG. 5. Number of formants ($nR_{s,n,f}$) in a sound spectrum at various bowing techniques (sound symbols used: ○ — g, x — d^1, □ — a^1, ■ — e^2, ● — d^3).

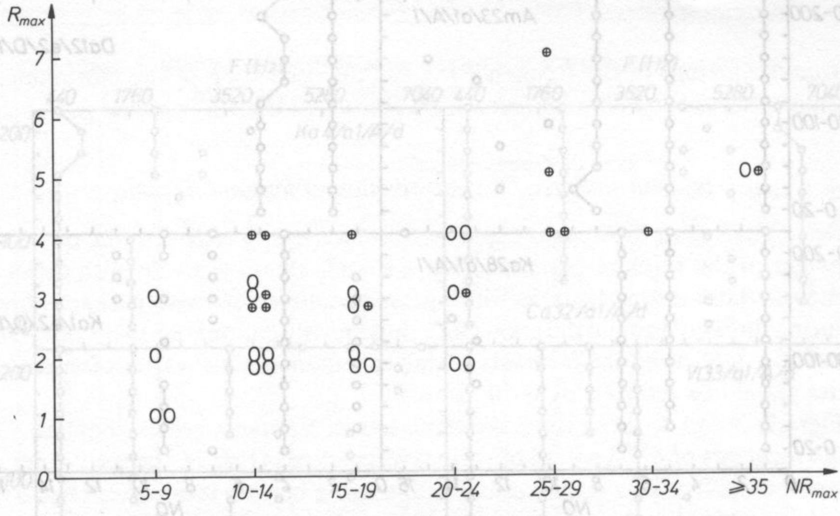

FIG. 6. Maximum numbers of formants ($R_{\max}$) during the time period 20 ms to 220 ms, in the sounds 1 to 35, with reference to the maximum ranges ($NR_{\max}$) ($R_{\max} = R_s + R_n$, O $- R_n = 0$, $\oplus - R_n > 0$).

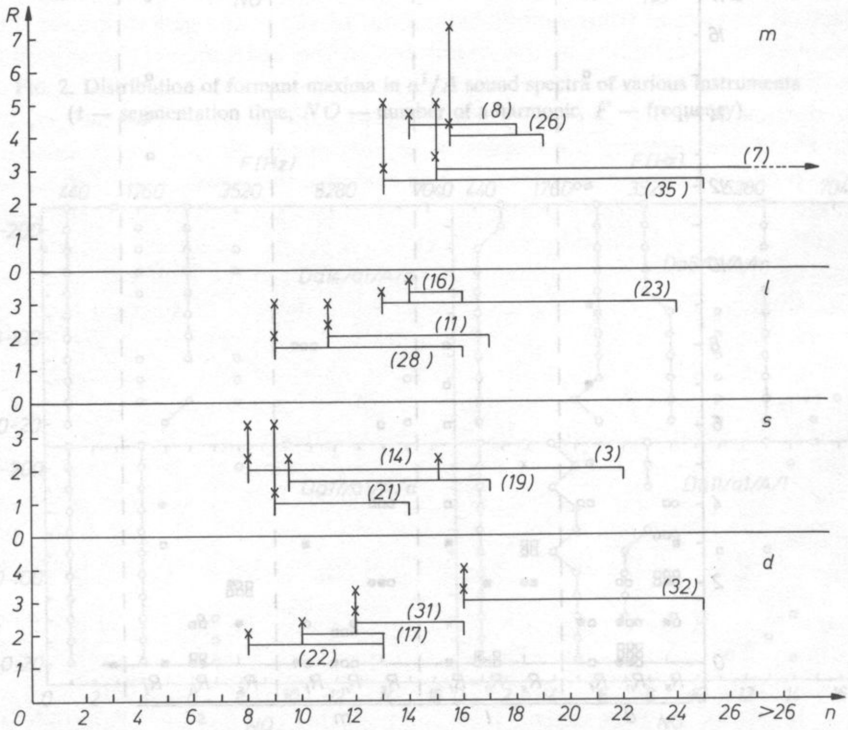

FIG. 7. Number of formants ($R = R_s + R_n$) in the dynamic spectra of a^1/A sounds during the time period from 20 to 220 ms (n — number of the harmonics corresponding to a spectral range, ⌐¬ span of a spectral range, ↨ overall range of the formants variability.

techniques. Only in the spectrum of one of these sounds, excited with martele technique (#26), the number of formants oscillated between four and seven. In three spectra, of two martele-sounds and of one staccato-sound, this change reached three and in five spectra, two formants. These results indicate that, with detaché and legato bowing, the number of formants within the sound forming period is more steady than in case of staccato or martele.

c. *Changes of intensity level of formant maxima in the duration time of sound*

Table 4. Overall variations of amplitudes (ΔA) of R_s and R_n formants of a sound in the time period 20 to 220 ms (NO — tone number, font „orator" denotes R_n, ⇄ oscillations of frequency, $*$-NR larger than 16)

Tech-nique	Sound	ΔA [dB] Maximum localisation NO 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
m	a^1/A – 7	3				← 10				8				← 16		15	
	– 8	8→					7		3→					4			
	– 9	4			3			8→									
	– 26	3		2		5				6		5				13	4*
	– 35	8→					← 10		3→					4			
	e^2/E – 25			3		← 7					11→						
	d^3/E – 13		7				←10										
l	d^1/D – 10	3		4			7		8		3						
	a^1/A – 11	2				← 3		4→									
	– 16	1						3 →						5→			
	–23	2				6			3 →								
	– 28	0				5		4									
	e^2/D – 1	3			1			2		2							
	– 12		2			← 4											
s	g^2/G – 5			11		14 →							4				
	a^1/A – 3	24				20											
	– 14	11			16		21										
	– 19	35								22							
	– 21	17→				36 →								← 8			
	e^2/E – 24	15→		8→													
	d^3/E – 20		←33														
d	g/G – 2		11			10				7→							9
	– 29		5		4				← 6								12*
	– 30		10					11				3→					10*
	a^1/A – 17	4			7												
	– 22	9				16											
	– 31	2			11				8								
	– 32	8				5						10→				←12	
	– 33	6			14		3		2								
	a^1/G – 15	7			12												
	a^1/D – 4	4→			16→												
	– 18	10			7		10										
	e^2/E – 6				←11			14									
	– 34	6						7							4		7
	d^3/E – 27	3															

Table 4 comprises the amplitudes of formant maxima of R_s and R_n type (in brackets) and their positioning. The greatest variations in an overall formant pattern occur for the staccato sounds; the smallest are the changes are observed for the legato sounds. Also, the differentiation between particular sounds of each group is different. In case of staccato excited sounds it is larger than those of the legato origin. Amplitude of the first formant is the least variable, independent on the sound exciting process.

Table 5. Overall changes A of the partials NR with respect to a sound intensity level in 0 – 20 ms time-segment of dynamic spectrum of a^1/A sound of Dankwart's violin (font "orator" denotes formant maxima, t — segmentation time → NO above 12)

t [ms]	ΔA [dB]											
	NO											
	1	2	3	4	5	6	7	8	9	10	11	12
a) Da14 staccato												
20–40	5	2	0	6	−13	−2	0	9	3	3	−1	0
40–60	8	4	2	9	−7	−3	3	10	3	3	0	4→
60–80	10	4	2	10	−12	−2	2	9	2	2	0	—
80–100	10	4	3	9	−13	−3	3	3	1	−1	—	—
100–120	9	2	1	6	−21	−4	−2	−7	−3	−3	—	—
120–140	7	0	−2	3	−20	−6	−2	−2	−10	−5	—	—
140–160	5	−2	−6	2	−17	−7	−6	−1	−11	2	0	2
160–180	1	−7	−11	−1	−25	−7	−5	−6	−12	−6	—	—
180–200	−4	−11	−12	−6	−25	−20	−11	−15	−13	—	—	—
200–220	−11	−11	−11	−11	−30	−23	−12	−14	—	—	—	—
b) Da17 detaché												
20–40	0	0	−1	−2	−1	−12	0	0	0	0	−2	
40–60	0	−1	−2	0	−2	10	1	2	1	−2	−4	
60–80	1	0	−7	0	2	23	4	6	4	1	0	
80–100	2	1	3	0	−1	14	4	6	6	4	1	
100–120	2	2	0	2	2	13	1	4	3	2	0	
120–140	3	2	−2	2	2	15	1	4	0	0	0	
140–160	3	3	3	4	1	15	−2	5	6	5	0	
160–180	3	3	−3	5	4	19	0	6	5	2	−1	
180–200	4	4	0	5	5	19	−3	7	3	4	0	
200–220	4	4	11	5	4	21	−5	3	3	5	1	

In Table 5a, b and 6a, b the typical changes of the time-amplitude structure of the partials of a^1 sounds produced with various bowing techniques, are collected. All the formant maxima are emphasized with "orator" font. Several discontinuities can be seen in the time dependences of the maxima, e.g. #14 in Table 6a, #11 in Table 6b, #8 in Table 5a. The most stable formant patterns occur in "legato" group and the highest number of "flickering" formants, of the largest amplitude changes, can be found in "detaché" group. It does not rule out an existence of these patterns in other bowing techniques, but they appear most characteristically in legato and detaché.

Table 6. Changes of a intensity level ΔA of the partials NR with respect to the intensity level measured in 0–20 ms segment, of the dynamic spectrum of a^1/A sound of Dankwart's violin (font "orator" denotes the formant maxima, t — segmentation time, → NO above 15)

t [ms]	ΔA [dB]														
	NO														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
a) Da11 legato															
20–40	1	−1	4	2	2	−1	−1	3	3	5	5	0	0	4	0
40–60	1	2	5	3	3	−1	1	4	5	5	5	0	5	0	0
60–80	1	−2	7	2	1	−2	−1	3	4	7	2	0	0	4	0
80–100	1	0	6	1	1	−6	−2	4	7	4	5	0	0	4	0
100–120	1	−3	7	3	−1	−5	−4	6	6	−8	5	0	5	0	0
120–140	1	1	6	5	2	−4	−3	6	6	0	5	0	0	0	0
140–160	2	−1	8	3	1	−2	−4	6	7	8	0	0	0	0	0
160–180	2	2	8	6	3	−5	−2	7	6	8	0	0	0	0	0
180–200	2	−1	9	4	1	−6	−4	6	6	11	5	0	0	4	4→
200–220	2	3	7	7	3	2	−7	8	8	4	0	0	4	0	4
b) Da8 martele															
20–40	10	8	4	5	9	4	3	12	10	4	0	4	5	6	10→
40–60	14	9	5	1	7	4	0	12	12	3	4	2	8	8	2
60–80	13	11	−2	4	5	8	−11	16	11	8	5	5	8	10	−4
80–100	12	12	−5	4	7	8	0	16	12	9	4	4	9	9	−6
100–120	12	12	−14	0	6	8	−9	16	10	8	3	7	8	8	−5
120–140	12	12	−11	2	4	7	−2	17	7	7	1	3	6	1	−2
140–160	8	10	−5	0	−5	1	−3	14	2	2	−4	2	−1	5	−5
160–180	9	13	−4	6	1	7	1	17	7	4	−2	1	5	10	−1
180–200	8	13	−6	7	3	6	2	16	8	3	−2	−6	5	8	0
200–220	6	13	−5	8	4	6	5	17	8	4	-3	−6	4	5	−4

Some formants R, occur repeatedly on the same harmonic tones. One may expect, that these frequencies coincide with the resonant maxima of an instrument. Activation of these resonances, featured as the sound formants, depends on several conditions. Similarly to the spectral range, the amplitudes of formant maxima undergo continuous transformations in time. Only in few cases the formants change monotonically, following the same pattern in the whole frequency range.

d. Time development of a complete formant structure

Table 7 contains the times of the formation of R_s and R_n formant patterns within 20 to 220 ms time segment. The data from the first segment 0–20 ms were disregarded, because, as it frequently happens in this time span, a harmonic structure is not fully developed yet and a strong noise component is present. A formant pattern is regarded quasi-stable, when its maximum amplitudes change less than 5 dB; the time it takes to reach such a state is accepted as the time of the quasi-stabilization.

Table 7. Formation of R_s and R_n formant patterns within 0–220 ms timescale, (t_p — initial time of a formant, $t_s A$ — time of amplitude quasistabilization, $n_s A$ — unstable amplitude)

Tech-nique	Sound	t_p [ms] R_s	R_n	$t_s A$ [ms]
	a^1/A – 7	80	40	100
	– 8	20	—	nsA
	– 9	20	—	100
m	– 26	60	40	100
	– 35	60	—	100
	e^2/E – 25	20	60	60
	d^3/E – 13	20	—	80
	d^1/D – 10	20	—	80
	d^1/A – 11	60	—	40
	– 16	20	—	40
l	– 23	20	—	60
	e^2/D – 1	20	40	40
	– 12	20	—	40
	g/G – 5	20	40	nsA
	a^1/A – 3	40	—	80
	– 14	20	40	nsA
s	– 19	20	—	nsA
	– 21	20	—	nsA
	e^2/E – 24	20	20	nsA
	d^3/E – 20	40	—	nsA
	g/G – 2	60	—	120
	– 29	40	60	100
	– 30	40	40	140
	a^1/A – 17	20	—	60
	– 22	40	—	120
	– 31	20	—	140
d	– 32	60	60	160
	– 33	120	—	120
	a^1/G – 15	40	—	nsA
	a^1/D – 4	20	—	nsA
	– 18	60	—	nsA
	e^2/E – 6	20	—	nsA
	– 34	40	60	180
	d^3/E – 27	20	—	40

The time of a formant creation R_s, for the sounds under investigation, vary between 20 and 60 ms, except for one sound (#7) generated with martele technique, where it amounted to 80 ms and the sound #33, excited with detaché technique, where it was 120 ms. The non-stabilized formants developed during 40 to 60 ms, irrespectively of the bowing technique. The quasi-stabilization of the complete formant pattern can be attained within 40 ms. It only occurs with martele, legato and detaché techniques, but in the latter case, the spectral structure of four tones was not stable within 220 ms time span. Generally, the staccato sounds are not stable, as far as their amplitudes are concerned.

4. Conclusions

Results of the analysis of the dynamical spectra of 35 violin sounds, intoned with various bowing techniques, indicate that during the attack stage and their transition into a quasi-steady state to (0 to 220 ms), the observed structures undergo various modifications. These changes may be considerable and subsequently may influence the forms of tone perception. The obtained results positively verify the approach taken by POLLARD who, referring to the microstructure of musical tones, includes the changes of such features as pitch and loudness together with the effects of timbre in his definition of "microstructure" [16].

Following conclusions may be drawn:

1. Irrespective of the bowing technique used during the process of a violin sound formation (attack), structural changes occur in spectral range and the formant structure. As a rule, the harmonic structure is preceeded by as short period of anharmonicity. No correlation was found between the changes in the spectral range and the changes in formant structure.

2. Spectral range is an individual attribute of a signal. Namely, in the attack stage, changes of this range assume various forces. When staccato is used, a two-step form prevails: the spectral range increases very quickly, then gradually decreases. With other techniques these changes are individually divergent. The legato features the least diversified spectral ranges.

3. During the attack stage, separate formants undergo transformations, irrespective of their positioning. These transformations do not sustain a unified form of the whole arrangement within a sound. Formant maxima can be divided into three groups: stable, discontinuous and fragmentary, according to their continuity in time. Irrespective of the bowing technique, the first formant maximum is mostly continuous. Fragmentary maxima, most frequently occur at the higher harmonics of a signal. In the sounds excited with the technique detaché, these maxima are observed more often than with the other bowing techniques.

Positioning of the stable and/or discontinuous formant maxima on frequency scale, often (approx. 30%) undergoes deviations within two neighbouring harmonics. In the stage of the development of a signal pattern the number of formant maxima oscillates. This features is more frequent with staccato and martele techniques than with detaché and legato.

4. Amplitudes of formant maxima of all the sounds of violin, pass through numerous and diversified changes, of which the oscillatory changes occur most often. The variability of these maxima is most pronounced with staccato, and the smallest for legato technique.

5. Generally, the time of a formation of an individual formant does not exceed 60 ms, sporadically the upper limits reach higher values. With the three techniques: detaché, legato and martele, a quasi-stabilization of the whole formant pattern may already be reached after 40 ms. However, in the group of the investigated signals, the upper limit was 80 ms and 100 ms, for the legato and martele techniques, correspondingly. These times are longer than the time of initial transients (51 ms), chosen by MCINTYRE and WOODHOUSE in their attempt to simulate the martele-signals [3], in case of the detaché technique, the time required for the formant structure of separate sounds to reach quasi-stabilisation is individually, very diversified. CRAMER suggests, that initial transients in the case of legato are longer than with martele technique [3]. It may however, refer only to the process of a signal amplitude formation. When the structure formation is concerned, the obtained results of analyses indicate that the stabilization in the legato technique lasts shorter as compared to martele technique.

6. The above arguments point to an individual character exhibited by the ensemble of structural changes of a violin sounds intoned by the same technique, irrespective of which

technique is used. It is related to an simultaneous effect of various factors on the process of a signal formation. They are more numerous in the natural, bow excited sounds than in the acoustic characteristics of an instrument obtained with laboratory methods, since they also contain contributions due to "the violinist's menagerie", the term refered to by MCINTYRE and WOODHOUSE [11].

The obtained results elucidate the problem of the internal changes occuring in the spectral structure of natural sounds of a violin. They should be regarded as a guiding rule to further the studies of this domain of the microstructure of sounds of stringed instruments.

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