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ESTIMATION OF GUITAR SOUND QUALITY

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The described investigation was aimed at the determination of the subjective and objective quality of sound of four classic guitars. The investigation of the subjective sound quality — carried out in the Laboratory of Music Acoustics, Academy of Music in Warsaw — consisted of two parts: general and parametric. The following parameters was used: brightness, timbre dispersion over the instrument scale, fullness, carrying power, clearness, dynamics. The listeners were students and co-workers in this laboratory. Investigations of the objective quality carried out in Zwota (GDR) resulted in sound pressure level histograms — presented in 20 diagrams for 20 frequency bands covering the full range of sound frequencies produced by the investigated instruments. The analysis of these histograms shows a significant correlation with the results of the subjective quality estimation.

1. Introduction

Among investigations of music instruments, which constitute a large part of acoustics — the examinations of string instruments, particularily violins, have an important place. These investigations concern also other string instruments, including guitars. Most measurements were carried out in order to determine improvements of the instrument design, essential to make the instrument better in view of its physical parameters and sound quality. It is obvious that physical properties, or even mechanical properties, are closely related to the sound quality of a given instrument.

However, many investigations concerned only the measureable guitar parameters. The resonance box and its properties, as a secondary source, were the main objects of interest. It appeared that the frequency characteristic of the sound radiated by the box contained, in its lower range, several resonances (formants) which significantly influenced the quality of sound. In the frequency range up to 800 Hz, these formants are clearly perceptible and can be simply investigated. The important problem, which presently is given a great deal of attention, is the location of these resonances (f_r) and their width (Q), peak level and level exceeding the rest of the signal. Resonances of the top plate were investigated widely. For example, [8] constructed systems of harmonic oscillators moving a piston, acting as individual sources, with a unipolar sound radiation. Every oscillator corresponds to one formant in the frequency response. Investigations conducted on 5 guitars have proved a significant correlation of the experimental results with the frequency response obtained theoretically from the analysis of a system of several oscillators. The author stated, that in the frequency range up to 800 Hz the parameters of 4–6 harmonic oscillators are sufficient. This procedure is much simpler that the investigation of the frequency response of the guitar box. One of CHRISTENSEN'S earlier works [6] was concerned with the first two guitar resonances only. These resonances were defined as the result of overlapping of the fundamental vibration of the top plate and the Helmholtz resonance of air inside the guitar box. Also in this case a theoretical model of the frequency characteristics in the low frequency range was proposed. It was found that the Helmholtz resonance was not equivalent with the air resonance. The Helmholtz resonance appeared as an antiformant between the first and second formant of the plate. The proposed model (oscillator design obtained on the basis of the Newton equation) precisely described the variation of the sound pressure level and the motion of the top plate of the guitar in terms of frequency. In another paper, [7] investigated the middle frequency range. The signal was recorded and than analysed with the application of the Fourier transform, in order to obtain the acoustical power density spectrum (*APDS*). Through averaging the levels in 1/3 octave bands and calculating the energy distribution, a curve with many informations about the sound, was achieved. This curve usually has the same characteristic jump-growing shape (the jumps are the regions of succeeding resonances) for every instrument. The greatest amount of energy comes from the 224–445 Hz range (this leads to a conclusion that it is a very important range for guitar sound quality). The following distinct jump occurs about 400 and 550 Hz — for the III and IV resonance. In this last range about 50 per cent (or more) of the energy is radiated. This accounts for the main interest in the low and medium frequency ranges (to about 800 Hz) in further investigations.

Among others, also CALDERSMITH [5] investigated the problem of vibrations of the plate and the air mass contained in the resonance box. This research also resulted in a theoretical model of the reflective casing, which was physically applicable and convincingly determined the most important parameters of the investigated box – the location and width of the fundamental set of two resonances (of plate air). The casing dimensions and the material it was made of, have been taken into account. The model also pointed out the significance of the location of the rose in the plate, in relation to the formant location in the frequency scale (this relationship results from the influence of air vibrations on the complete characteristic of sound radiation).

Similar research was also conducted by FIRTH [10], [9] and JANSSON [12], [13].

In the first mentioned work, Jansson discussed acoustical tests of vibrations of the guitar top plate. Vibrations modes, corresponding to succeeding formants of the frequency characteristic, were studied with the application of holograph interferometric method. This method leads to the determination of the resonance frequency, *f*, and the quality factor, *Q*. The characteristic obtained from acoustical measurements was compared with interferograms. Acoustic investigations were conducted with the application of 6 various box excitation points and 6 (different) measuring points of the characteristic. It was stated that the frequency of individual formants obtained from these two methods are constant with an error not exceeding 1 per cent, while *Q* – with an error not exceeding 13 per cent. Therefore, both values can be achieved from acoustical measurements, on condition that the measuring points of the characteristic are carefully chosen.

In order to explain acoustical properties of resonance holes another series of investigations were carried out. Boxes of various shapes have been investigated. The frequency response of the vibrations of air contained in these casings, was measured. It appeared that guitars and violins had the same vibration modes and generally they corresponded with rectangular and cylindrical casings. The resonance density did not depend on the shape of the box, if the volume, wall surface and lengths of the edges were identical. On the other hand, the density calculated from geometrical data for guitars, differed from the real density by 60 per cent. Whereas, vibration modes changed even at the slightest change of the box shape.

In his paper of 1977, FRITH [10] described a physical model representing the functioning of a guitar. For the reason to construct this model, the following measurements were carried out: the resonance frequency (defined as the formant at 0 Hz – the Helmholtz resonance), the shape of vibration modes (with the application of Chladni figures), input admittance in the central point of the bridge (in the first and second resonance range), and the input sound pressure level and its phase.

All mentioned above papers were concerned exclusively with the physical aspect of the vibrations of the guitar resonance box. Methods of acoustic measurements and various models allowing mathematical calculation of various parameters, have been hitherto described.

The works of KRÜGER [15], MEYER [17] and JAROSZEWSKI, RAKOWSKI, ZERA [14] dealed with a different aspect of the problem. However, KRÜGER still taked up the problem of frequency response of the top plate vibrations, but he conducted research on 20 guitars, which were subjectively rated as good, middle and bad. He tried to relate certain characteristic estimations of physical parameters of instruments to their individual ranks (e.g. a master guitar displays a distinctly higher sound pressure level from any other instrument in the 200–800 Hz range and somewhat less in the range of the so-called "bass"). In the course of his experiments KRÜGER introduced variants of the design structure of the top plate and studied their influence on the sound character. He reached a conclusion that at a constant energy the lesser the losses during the process of bending a plate (during vibrations) and the lesser its rigidity, the greater the vibration amplitude (and thus the sound radiation level for a given frequency).

Energy losses caused by these two factors decrease with the decrease of the plate thickness.

The other two papers described research concerned with the subjective evaluation of the guitar sound quality. JAROSZEWSKI et al. [14] limited their studies to one parameter, i.e. onset time. Subjective evaluations were carried out by experts during individual 0.5–1.5 hour sessions. The sound arise time was measured from a perceptible moment of the beginning of the signal to the moment it reached 90 or 100 per cent of the maximal amplitude (in dependence on shape of arise). A comparison between the obtained results and the experts' evaluation showed distinct correlation between them. Instruments with longer attack were rated as a better. These better instruments had also a lower relative dispersion of the onset time values (30 sounds for 13 guitars have been investigated). MEYER'S paper [17] includes more criteria. It was aimed at finding such resonance properties of the instrument, which would significantly influence its quality. 15 guitars have been studied and 40 persons have subjectively evaluated instruments on the basis of an auditory test. Correlation of obtained rank arrangements of instruments with data obtained from various modifications of the frequency response was calculated (level averaging in 1/3 octave and wider bands of various ranges; determining formant levels and widths, as well as determining how much this range exceeds the rest of the frequency region; establishing the distances between the box resonances and the nearest sound, etc.). A distinct correlation was observed here between certain criteria of the physical and subjective quality evaluation. E.g. the high level in the 80–1000 Hz region occurred only in highly rated guitars — the better the instrument, the higher level of the third resonance (but a smaller width), the additional formant between the main formants was also a positive feature of the instrument.

In the final stage of these studies the correlation coefficient between the results of subjective and objective evaluation was calculated for all 20 parameters. The correlation was very high, namely $r = 0.88$, and excluding the guitar with an unstable pitch, it equaled $r = 0.97$. However, even only seven criteria gave a very high correlation coefficient of 0.85. It was found that for a high correlation between subjective and objective evaluation, the most important factors are: the level of third resonrence, level values in the 80–125 Hz 250–400 Hz and 315–500 Hz, and the occurrence of a formant between the first and second resonance. Unfortunately, during the investigations it appeared that there is a rather significant dependence on the kind of music played on the instrument. This to a certain extent shakes the universality of the achieved results.

It should be mentioned here that musicians always select instruments to the kind of music they are to play (solo, accompaniament, melody or rather harmonic structures).

The experiment presented in this paper, performed by KAM in Warsaw and the IfM in Zwota (GDR), was aimed at similar goals as the last discussed paper. 4 guitars have been subjectively rated (auditory test). The comparison and correlation of the achieved results were the final goal. Investigations of the subjective sound quality were carried out in the Laboratory of Music Acoustics at the Academy of Music in Warsaw, while the objective parameters were measured in IfM in Zwota (GDR).

2. Experimental materials

Guitars for investigations were chosen only from among concert instruments of medium quality, corresponding to a class of higher quality instruments produced in large-scale. However, due to various designs, certain differences in sound timbre were expected. Instrument no. 1 (test guitar, produced by a violin maker) was a hand-made experimental model, which had a modified resonance plate in the bridge region, in order to improve radiation of low frequencies. Other guitars were standard instruments produced by industry and widely sold. Instrument no. 2 was one of the "Resonata" models, till now produced by VEB Musima in Markneukirchen. Instrument no. 3 was a new achievement, named "Musima Classic", model 136. The new range of products from the "Classic" series was developed in cooperation between VEB Musima and Institute of Music Instruments Construction (IfM) in Zwota and it replaced the "Resonata" assortment. It had an optimised radiation power in comparison with previous models. Furthermore, this new assortment had a vaulted plate.

Instrument no. 4 (Marlin MC 315) has been included in tests as an instrument for comparison, due to its high acoustic value distinguishing it from other instruments produced by industry.

3. Subjective evaluation — arrangement of tests

The test was constructed under the method of comparing in pairs. Excerpts of recordings of individual instruments were grouped in pairs, so every instrument was compared with every other instrument. This way six pairs were formed (from four elements).

However, since an arrangement of two instruments was presented two times — in a different sequence every time (*AB*, *BA*) — there were twelve test items. Their sequence in a test was randomly chosen. Such a twelve — task test constituted one out of three parts of the whole test material. These parts differed from each other in the sequence of test items and, first of all in the music material, i.e. in every part a different music composition was used: in part I — Preludium no. 1 by Villa-Lobos, in part II — the second variation from the Variation on Mozart by Ferynand Sor, in part III — Rondetto by Napoleon Coste.

4. Conduction of tests

The subjective auditory estimation was divided into two parts:

1. So-called general evaluation (general impression) of the instrument quality;

2. Estimation of six subjective parameters: brightness, timbre dispersion over the instrument scale, fullness, carrying power, clearness (clarity, absence of disturbances and deformations) and dynamics (dynamic range).

In the second part the listeners were to estimate which instrument posseses a given feature in a greater extend. That is, which one, within the pair, is brighter, has better dispersion, has better sound fullness etc. If the instruments differed greatly the listener was to give two points, when they differed less-one point. The instrument with a given feature estimated lower, obtained zero points. In the case of the general evaluation (part I) listeners gave one or two points to this guitar out of a pair, which they liked more. This evaluation was performed on the whole test material — on all three parts — while every parameter was rated with the application of only one part of the test. The brightness and timbre dispersion were evaluated only for guitars in the first part of the test; fullness and carrying power — in the second part; sound clearness and dynamics — in the third part. Therefore every listener listened to the whole test two times: first time — applying the uniform criterion of the general evaluation and second time — applying the criterion of the parametric estimation, different for every one of the three parts of the test.

The group of listeners consisted of 24 persons. These were students and workers of the Academy of Music in Warsaw. Two persons were students of a guitar class of the instrumental faculty, the rest of group consisted of students and graduates of the Faculty of Sound Recording.

The test was reproduced on a Revox B 77 tape recorder and listeners were equipped with SN 60 earphones.

5. Results

In the results analysis first of all it had to be checked whether the kind of music significantly influenced the results. If the general evaluation gave by listeners would depend on the character of the stimulus, then it would not be possible to sum up the results — points obtained for every guitar in individual parts of the test, and the parametric estimation should have to be conducted for all three parts separately. Moreover, due to the interdependence of results and the test itself, it would be impossible finally to rank the instruments in a certain order. In order to state, whether there is such a dependence, a two-factor analysis an variance was performed [4]. ANOVA table is presented in

Table 1. Complete results of two-factor variance analysis — general estimation

Type of variability	ϑ	Sum square	σ^2	F	$F(\alpha, \vartheta_I, \vartheta_{II})$	
					1%	5%
A (test)	2	0.337	0.1685	0.0543	4.68	3.03
B (guitars)	3	357.674	125.225	40.363	3.85	2.63
AB	6	427.857	71.3095	22.984	2.86	2.13
E	276	856.292	3.1025			
total	287	1660.16				

Tab. 1. The application of such two-factor analysis was possible under an assumption of a uniform group of listeners. Without such an assumption a multifactor analysis would be necessary, where the listeners would be the third variable. This would seriously complicate the calculations. But since all listeners were workers or students of the Academy of Music mainly from the Faculty of Sound Recording, the group could have been considered as uniform and the differences between individual persons could have been neglected.

An additional information about the group of listeners was obtained by calculating the reliability coefficient for every listener. As the test was done in such manner, that it could be easily divided into two halves (all pairs of instruments occurred in both halves, but in a reversed sequence), then we could apply the RULON's equation [11]:

$$r = \frac{\sigma_d^2}{\sigma_x^2}$$

σ_d^2 — variance of differences between the two halves, σ_x^2 — variance of all test results, which is a useful measure of reliability.

All data from every listener are presented in tables, confronting results of corresponding pairs (e.g. 3–4 and 4–3, 1–2 and 2–1, ...). Then, both variances and reliability (r) were calculated by choosing randomly external or internal columns.

Finally, the guitars were ordered on the rank scale according to the estimation of the subjective quality. To this aim points given to every instrument by all listeners were added up/an instrument could have obtained a maximum amount 864 points: 6 presentations of the instrument $\times 24$ listeners $\times 2$ points $\times 3$ parts of the test (Table 2). Also the mean values of estimations were calculated — their arithmetic mean, $M = \Sigma X/N$, and the standard deviations, $\sigma = \sqrt{\frac{\Sigma x^2}{N}}$ (Table 3, Fig. 1).

ΣX — the sum of points of all listeners,
Σx^2 — the sum of squares of deviations of every result from the mean,
N — number of results,
M — arithmetic mean.

Table 2. Classification of the instruments on the rank scale — general estimation

Guitars	Points	Rank
1	232	III
2	136	IV
3	350	I
4	313	II

1 — master instrument (Markneukirchen)
2 — industrial guitar (Musima)
3 — investigated guitar
4 — Japanese industrial guitar (Marlin MC 315)

Table 3. Means and standard deviations for points obtained by all instruments — general estimation

Guitars	M	σ
1	3.222	1.863
2	1.888	1.939
3	4.861	2.519
4	4.347	2.124

On the basis of this data we can set instruments in an order from the "best" to the "worst", but we still do not know anything about the absolute differentiation of these instruments, or what the "best" and "worst" means. For in the case of a subjective rating we can not fix an absolute zero or any unit, which would determine how many times one instrument is better (worse) than another, we can only place instruments on a rank scale. Therefore, the only information that could been obtained here, was the significance of differences between mean values for individual instruments. To this aim a Student's t test was applied for differences between non-correlated means in samples of equal quantity,

$$t = \frac{M_1 - M_2}{\sqrt{\frac{\Sigma X_1^2 - \Sigma X_2^2}{N(N-1)}}},$$

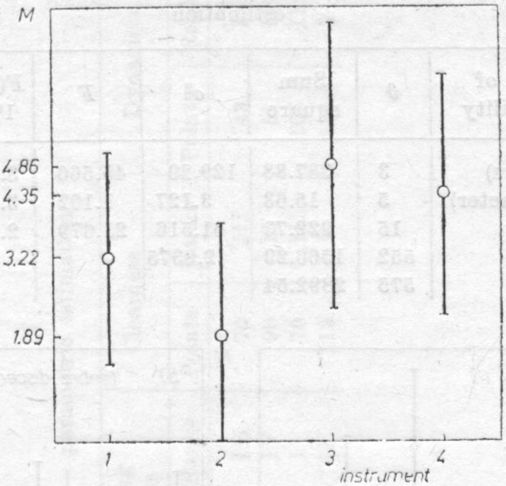

Fig. 1. Means and standard deviations – general estimation

M_1, M_2 – means in two samples (in this case – mean results for two instruments), ΣX_1^2, ΣX_2^2 – sums of squares in both samples.

Obtained quantities show which guitars significantly differ from each other, and for which these differences may be neglected (Table 4).

Results of parametric estimations were processed in the same way.

Table 4. Significancy of differences between means for individual instruments – general estimation

Guitars	t	Significance level
3–1	2.09	0.05
2–3	2.91	0.01
4–2	2.8	0.01
1–2	2.45	0.05

1 – master instrument (Markneukirchen)
2 – industrial guitar (Musima)
3 – investigated guitar
4 – Japanese industrial guitar (Marlin MC 315)

First, it was checked with the application of a two-factor analysis of variance whether the obtained differentiation of results is caused by differences between instruments or criteria (parameters) according to which listeners conducted the estimation. Results of the analysis are presented in Table 5.

Table 5. Results of the two-factor variance analysis — parametric estimation

Type of variability	ϑ	Sum square	σ^2	F	$F(\alpha, \vartheta_I, \vartheta_{II})$ 1%	5%
A (guitars)	3	387.88	129.29	45.566	3.82	2.62
B (parameter)	5	15.63	3.127	1.102	3.05	2.23
AB	15	922.73	61.516	21.679	2.12	1.71
E	552	1566.29	2.8375			
total	575	2892.54				

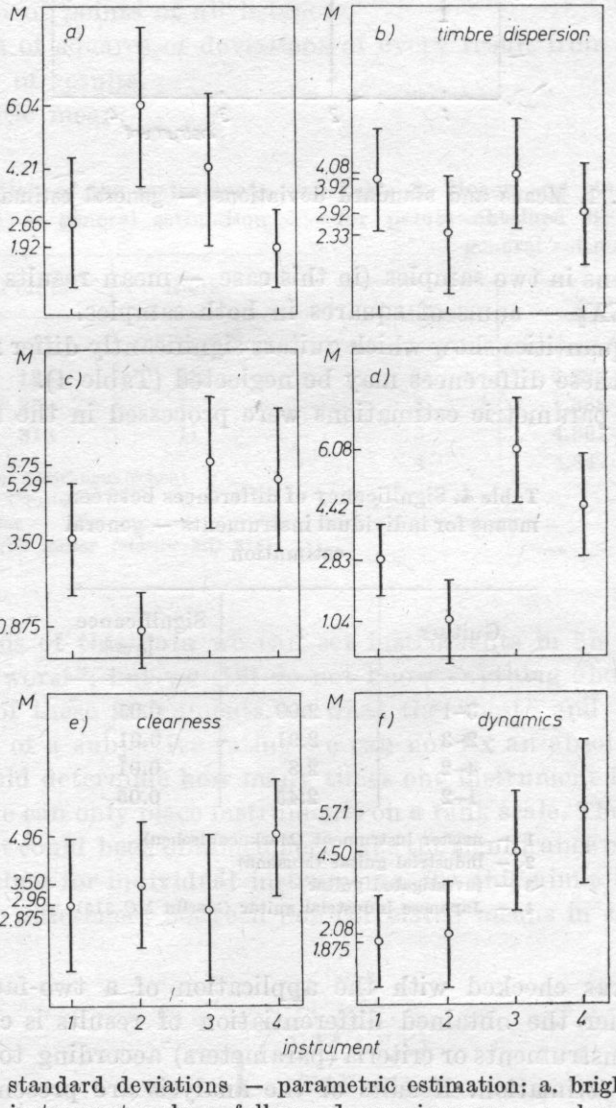

Fig. 2. Means and standard deviations — parametric estimation: a. brightness, b. timbre dispersion over the instrument scale, c. fullness, d. carrying power, e. clearness, f. dynamics

Table 6. Classification of the instruments on the rank scale – parametric estimation

Parameter	Brightness		Timbre dispersion		Fullness		Carrying power		Clearness		Dynamics	
Guitars	Points	Ranks	Points	Ranks	Points	Ranks	Points	Ranks	Points	Ranks	Points	Ranks
1	64	III	98	II	84	III	70	III	70	III	43	IV
2	146	I	54	IV	21	IV	24	IV	90	II	51	III
3	100	II	99	I	138	I	145	I	70	III	109	II
4	46	IV	68	III	130	II	116	II	119	I	138	I

1 – Master instrument (Markneukirchen)
2 – Industrial guitar (Musima)
3 – Investigated guitar
4 – Japanese industrial guitar (Marlin MC 315)

Table 7. Means and standard deviations of individual data for all of instruments — parametric estimation

Parameter	Brightness		Timbre dispersion		Fullness		Carrying power		Clearness		Dynamics	
Guitars	*M*	σ	*M*	σ	*M*	σ	*M*	σ	*M*	σ	*M*	σ
1	2.66	1.88	3.916	1.5	3.5	1.615	2.833	1.007	2.958	1.88	1.875	1.329
2	6.04	2.349	2.333	1.76	0.875	1.115	1.041	1.232	3.5	1.841	2.083	1.585
3	4.21	2.206	4.083	1.639	5.75	1.916	6.083	1.471	2.875	2.132	4.5	1.719
4	1.92	1.176	2.516	1.442	5.291	2.095	4.416	1.501	4.958	1.731	5.708	2.095

1 — Master instrument (Markneukirchen)
2 — Industrial guitar (Musima)
3 — Investigated guitar
4 — Japanese industrial guitar (Marlin MC 315)

Table 8. Significancy of differences between means for individual instruments — parametric estimation

Parameter	Guitars	*t*	Significance level
Brightness	1–2	2.24	0.05
	3–4	2.1	0.05
	2–4	2.89	0.01
Timbre dispersion	all differences insignificant		
Fullness	2–3	3.77	0.01
	2–4	3.62	0.01
	1–2	3.08	0.01
Carrying power	1–3	2.25	0.05
	2–3	3.75	0.01
	1–2	2.53	0.05
	2–4	3.29	0.01
Clearness	all differences insignificant		
Dynamics	2–4	2.63	0.05
	1–4	2.84	0.01
	2–3	2.12	0.05
	1–3	2.37	0.05

1 — Master instrument (Markneukirchen)
2 — Industrial guitar (Musima)
3 — Investigated guitar
4 — Japanese industrial guitar (Marlin MC 315)

Also for the parametric estimation instruments were classified on rank scales according to the possession of a given feature from the brightest to the least bright, from most to least dispersed, etc. (Table 6, 7, Fig. 2). The significance of differences between the mean value of points obtained by individual instruments was checked with application of the Student's *t* test. These results are presented in Table 8.

6. Conclusions concerning the subjective estimation

The evaluation reliability of listeners was found to be in the greater part high. Only for six persons the r coefficient dropped below 0.8, while for seven persons it exceeded 0.95. The high reliability consistently chose the better (according to them) instrument; that they had a certain constant quality criterion according to which they rated instruments. On the basis of these coefficients also a conclusion can be drawn that the sequence of instruments in a pair test item is not significant in such tests. The reliability coefficient, calculated from the RULON'S formula brings information about the conformity between both halves of the test. Since in this case, in the second half the sequence of stimuli was reversed in comparison to the first half (*AB* and *BA*) and in spite of that listeners chose the same instrument, then it means that it was not significant which one occurred as the first and which as the second within the pair.

Another important matter was to check whether the results were influenced by the kind of music played on tested instruments. Results of the analysis of variance, presented in Table 1, bring an answer to this question. It was found that individual guitars were the only significant factor – the value F is higher from the critical value of the 1 per cent level. Whereas, the kind of music material, on which the evaluation was conducted, was statistically insignificant.

Therefore, it was possible to carry out the parametric estimation on only one out of three parts of the test – not on the whole test. Obtained results can be considered representative.

The analysis of variance, where guitars are one factor and the subjective parameters – the second, give an interesting information. It was stated that results was significantly influenced by the evaluation criterion on 1 per cent, level while the variability caused by instruments was insignificant. This can mean that the differences between guitars in respect to a certain feature are small and that every feature classifies instruments differently. E.g. the guitar which achieved the most points in respect to the criterion of brightness, will not have the best timbre dispersion or carrying power. These suppositions have been confirmed by the number of points achieved by each guitar. Rank of instruments in respect to particular parameters are shown in Table 6. And indeed various features classified instruments differently. The classification in respect to the criterion of brightness proved itself to be the least similar to other parameters, while the fullness and carrying power gave the same results. A similar classification was obtained in respect to the timbre dispersion over the instrument scale; slightly different in respect to dynamics and clearness. However, further conclusions could not be drawn from these results before it was stated whether the differences between instruments with succeeding ranks are significant. It was stated that only some of them are significant. The dispersion over the instrument scale and clearness were found insignificant as a parameter-even the difference between the first and fourth rank was insignificant. The difference between the first and second rank is insignificant for all criteria. In respect to fullness, one instrument (no. 2) proved itself distinctly worse from other instruments. The differences between this and any other instrument are significant on the 1 per cent level. All other differences (between guitars with ranks: I, II and III) were insignificant. Therefore, in respect to fullness two groups can be formed: first — including guitars no. 1, 3 and 4, second — guitar no. 2. In respect to the criterion of dynamics, differences between the guitar with rank I (no. 4) and guitars with ranks III (no. 2) and IV (no. 1), and between guitar with rank II (no. 3) and guitars with ranks III and IV, were proved to be significant. This way two classes were obtained: the first one includes instruments no. 3 and 4, the second — no. 1 and 2. Differences between no. 1 and 4 are significant on the 1 per cent level the other — on the 5 per cent level.

It was difficult to determine similar classes in respect to the criteria of carrying power and brightness. In respect to carrying power, the instrument with rank IV (no. 2) distinctly differed from others, while first three ranks formed one class. The difference between the first and third rank (no. 3 and 1) is significant on the 5 per cent level. The classes in respect to brightness were slightly different. The first rank (no. 2) constitutes one class the second (no. 3) and third (no. 1) — the second class, the fourth rank — the third class. The differences between instruments no. 2 and 3, and no. 1 and 4 are insignificant. The difference between the I and IV rank is significant on the 1 per cent level while the others — on the 5 per cent level. The final classification of instruments according to subjective parameters is presented in Fig. 3.

The criterion of the general evaluation gives another, different classification. In this case guitar no. 2 proved itself to be the worst. It significantly differs on the 1 per cent level from guitars with the I (no. 3) and II (no. 4) ranks. In relations to the guitar with the III rank (no. 1), the difference is significant on the 5 per cent level. Thus, in this case three classes of instruments have been formed: first — including guitars no. 3 and 4, second — no. 1, third — no. 2. But it has to be remembered that guitars no. 1 and no. 4 do not differ significantly (Fig. 4).

As it can be seen from the above discussion, the general evaluation criterion classifies guitars in the same way as the criterion of carrying power, fullness and timbre dispersion (because the reverse classification of guitars no. 1 and 4 is not significant). The criterion of dynamics classifies them in a very similar way — only the change of ranks of guitars no. 1 and 2 is important, because the difference between these instruments is significant according to the general estimation. The classification in respect to the criterion of sound clearness is different, but it does not distinguish or disqualify any instrument, therefore it can be left out of account. Instead the different sequence of instruments obtained

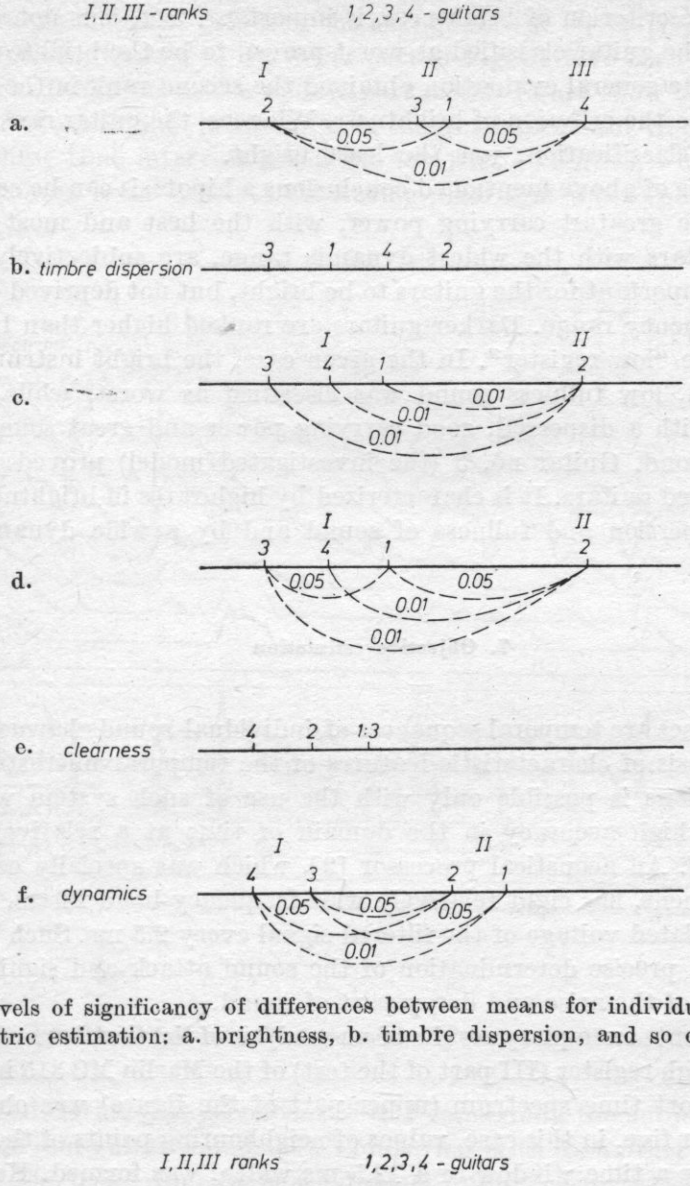

Fig. 3. Levels of significancy of differences between means for individual instruments — parametric estimation: a. brightness, b. timbre dispersion, and so on as in Fig. 2

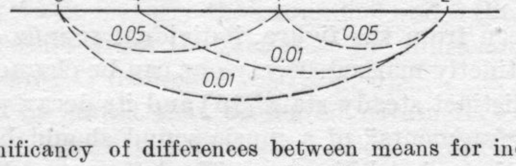

Fig. 4. Levels of significancy of differences between means for individual instruments — general estimation

according to the criterion of brightness, is important. Yet, it is not a reversed classification. The guitar classified as worst proved to be the brightest, but the best guitar in the general evaluation obtained the second rank in the classification in respect to the criterion of brightness. Whereas, the guitar ranked second in the general classification, was the least bright.

On the basis of above mentioned conclusions a hipotesis can be set up, that guitars with the greatest carrying power, with the best and most dispersed sound, and guitars with the widest dynamic range, are subjectively rated as the best. It is important for the guitars to be bright, but not deprived of fullness in the low frequency range. Darker guitars are ranked higher than bright guitars without the "low register". In the given case, the bright instrument with a non-dispersed, low fullness sound was classified as worst, while the least bright guitar with a dispersed, good carrying power and great sound fullness was ranked second. Guitar no. 3 (the investigated model) proved itself best among four tested guitars. It is characterized by high rates in brightness, carrying power, dispersion and fullness of sound and by a wide dynamic range.

7. Objective estimation

Music phrases are temporal sequences of individual sounds harmonic structures. An analysis of characteristic features of the temporal microstructure of observed functions is possible only with the use of such system which give a particularily high accuracy in the domain of time at a relatively narrow frequency band. An acoustical processor [2], which was specially constructed for this experiment, has eight relatively wide frequency band filters. It processes the demodulated voltage of the filtered signal every 2.5 ms. Such a high accuracy allows a precise determination of the sound attack and significant dynamic features of the arise and decay part of sound.

Fig. 5 presents exemplary results of an analysis of the first bars of a melody played in the high register (III part of the test) of the Marlin MC 315 instrument (no. 4). The short time spectrum (upper part of the figure) was obtained by putting together five, in this case, values of neighbouring points of the envelope curve. This way a time window of a 12.5 ms width, was formed. However, in order to accurately catch the sound attack, the differences between neighbouring values of the envelope curve are presented in a 2.5 ms time units (in the lower part of the figure).

As it can be seen from the figure, individual sounds of the phrase have been clearly and distinctly marked. Every one can be characterized by its onset time, more or less distinct steady state [16] and its decay phase. According to Fig. 5 these three "fragments" of a music sound should be clearly presented in the form of two-dimensional diagrams. The left part of Fig. 6 presents arise phase diagrams. Maximal values of the changes of the envelope curve (i.e. level "peaks" appearing clearly in the lower part of Fig. 5) have been marked on the ordinate axis. Diagrams in the middle part of this figure show the steady state for the individual sounds in the form of maximal spectrum values. Thus, they represent these time intervals (from the top part of Fig. 4), which correspond to the maximum level value. A measuring algorithm was applied here, which

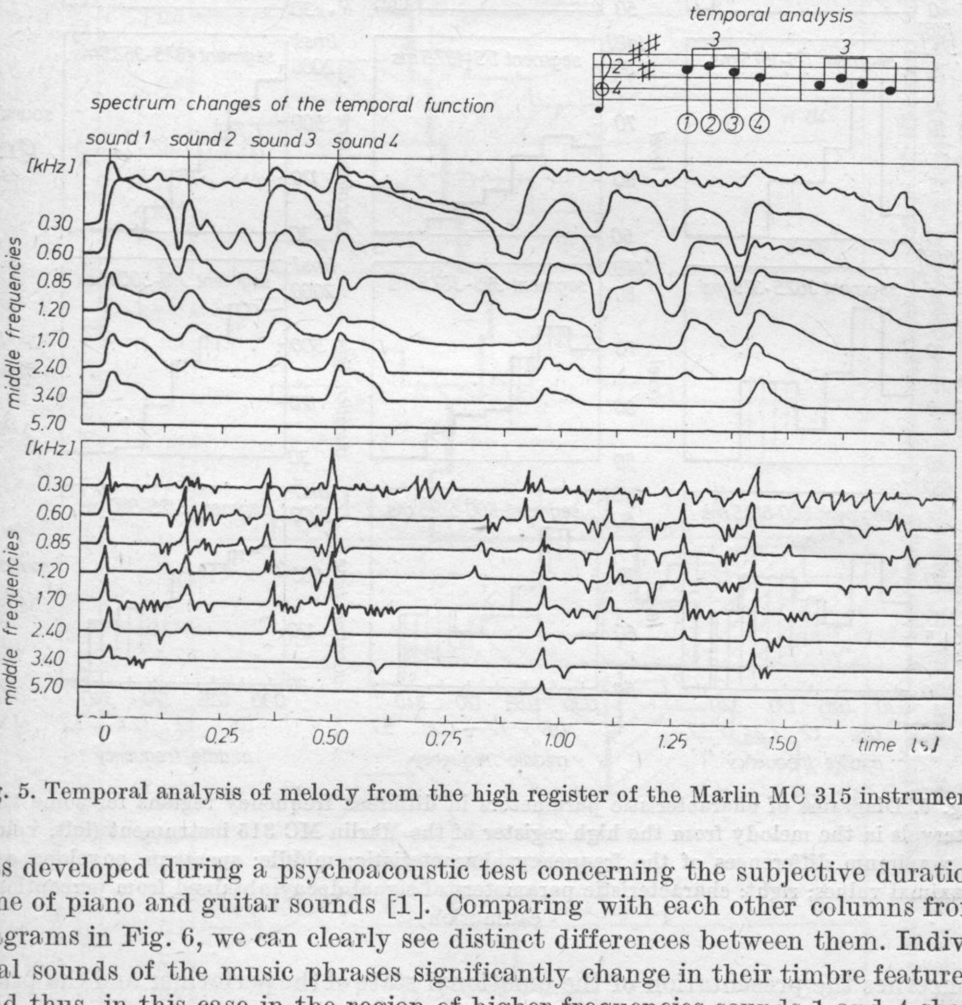

Fig. 5. Temporal analysis of melody from the high register of the Marlin MC 315 instrument

was developed during a psychoacoustic test concerning the subjective duration time of piano and guitar sounds [1]. Comparing with each other columns from diagrams in Fig. 6, we can clearly see distinct differences between them. Individual sounds of the music phrases significantly change in their timbre features. And thus, in this case in the region of higher frequencies sounds 1 and 4 show more distinct characteristic features than sounds 2 and 3 (lined areas in Fig. 6). Most probably this results from the fact that the musician wanted to accent these two sounds (1 and 4) (compare with Fig. 5).

Generally it can be stated that presented parameters of a chosen sound give an important ectosemantic information about music, i.e. such an information which can not be obtained directly from the score. In particular this

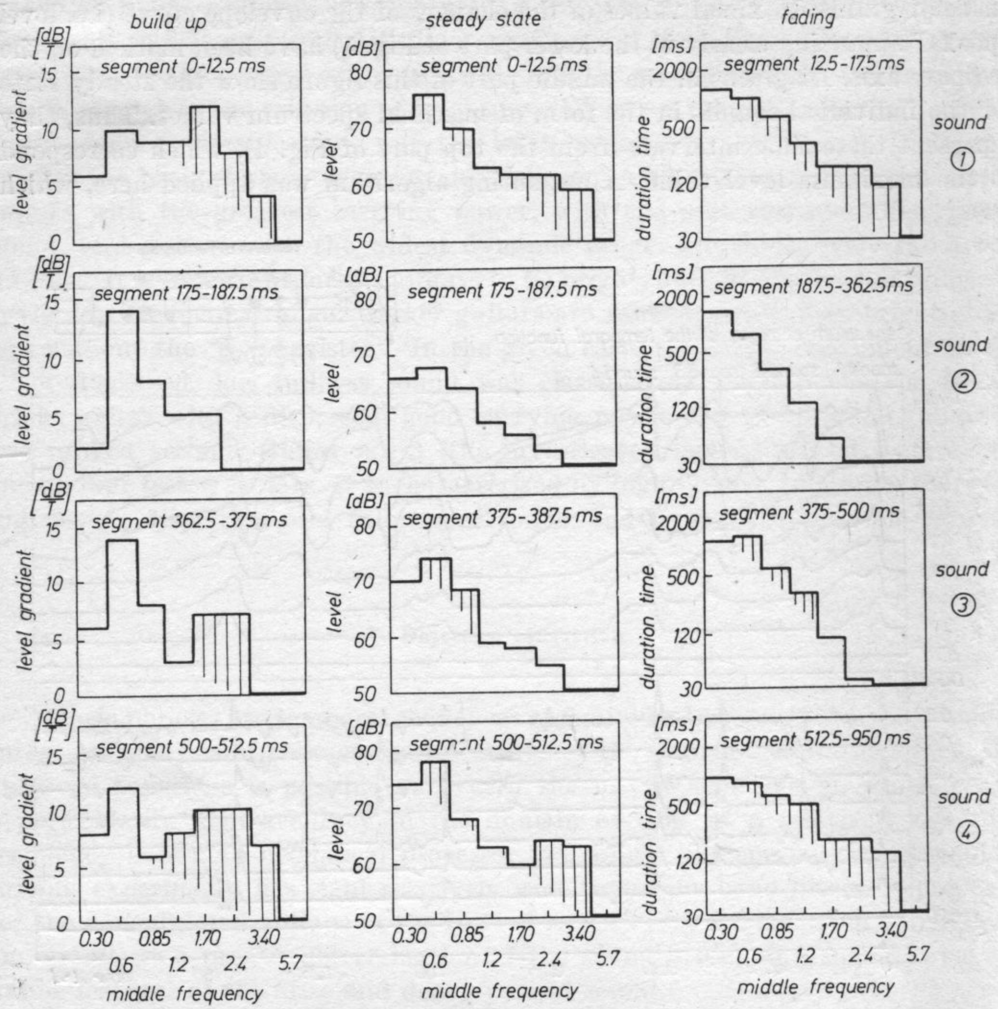

Fig. 6. Diagrams of characteristic parameters in different frequency regions for some time intervals in the melody from the high register of the Marlin MC 315 instrument (left: values of maximum differences of the frequency characteristic; middle: spectrum envelope over maximal values; right: characteristic parameters of signal decay obtained from perceptional estimation)

concernes the presentation of the emotional state of the performer and the problem of emphasis in music. The "inner states" of the musicians are converted through analogue coding into acoustical parameters of the sound. The emotion causes an increase of the size and power of adequate features. When the emotion passes these parameters weaken until they fade in the noise. The possibility of determining such slight changes of these parameters can be recognized as a significant criterion of the sound quality of music instruments. Beside the estimation of these sound features, based on computer calculations, also typical identifi-

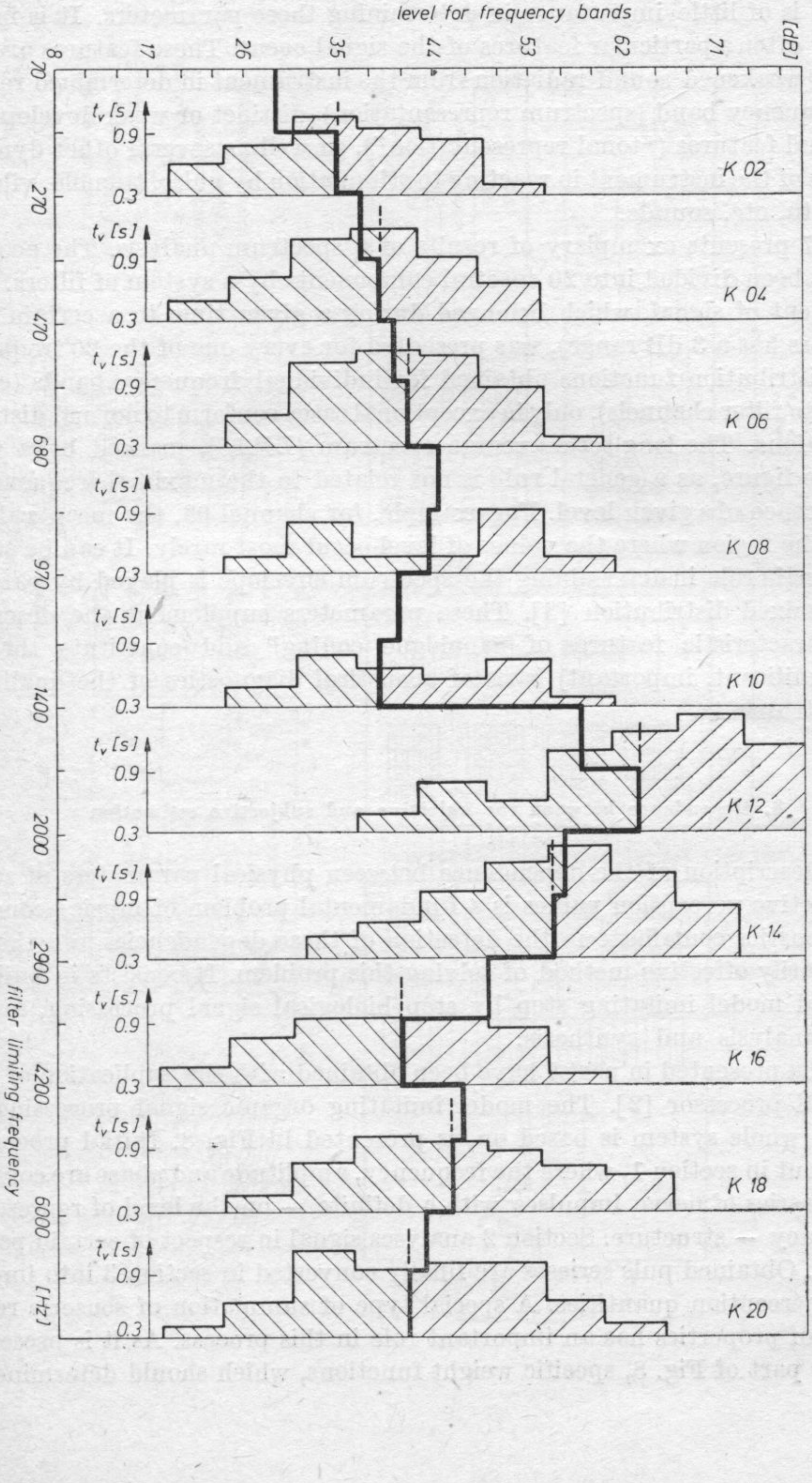

Fig. 7. Example of statistical representation of the spectrum. Thick line: long-time spectrum of the averaged data; individual histograms: frequency of occurrance of particular sound pressure levels in separate filter bands

cation — diagnostic parameters of instruments are significant. The sequence of sounds is of little importance in determining these parameters. It is important, how often a particular features of the signal occur. These features are amplified or weakened sound radiation from the instrument in determined regions of the frequency band (spectrum representation), distinct or weak development of the tonal features ("tonal representation"), as well as several other dynamic properties of the instrument in reacting to stimulation by pulse, tremolo, vibrato, portamento, etc. sounds.

Fig. 7 presents exemplary of results of a spectrum analysis. The acoustic signal has been divided into 20 spectral components by a system of filters. A 10 sec fragment of signal, which belonged during a given time to a certain class (every class has a 3 dB range), was presented for every one of the 20 frequency bands. Distribution functions obtained for individual frequency bands (corresponding to filter channels), only in exceptional cases conform to normal distribution functions. The long-term average spectrum (*LTAS*), marked by a thick line in the figure, as a general rule is not related to the maximal frequency of the occurrence of a given level. For example, for channel 08, the mean value is found in the region where the values of level occur most rarely. It can be stated that the main role in determining the spectrum envelope is played by parameters of a mixed distribution [3]. These parameters supplement the described above characteristic features of "analogue coding" and constitute the real (main, significant, important) basis of acoustical diagnostics of the quality of music instruments.

8. Dependence between the objective and subjective estimation

The description of the dependence between physical parameters of sound and subjective perception values is a fundamental problem of music acoustics. Psychoacoustics contribute in the detection of these dependencies and there is a particularily effective method of solving this problem. It consists in building a technical model imitating step by step biological signal processing, on the basis of analysis and synthesis.

Results presented in part 7 have been obtained with the application of such a technical processor [2]. The model imitating organic signal processing, on which the whole system is based on, is presented in Fig. 8. Initial processing is carried out in section 1, where the frequency, amplitude and phase are converted into a series of nerve impulses with a definite — on the level of representation accuracy — structure. Section 2 analyses signal in respect of certain partial properties. Obtained puls serieses are finally converted in section 3 into impression and perception quantities. A special type of summation of sensoric representation of properties has an important role in this process. As it is presented in the top part of Fig. 8, specific weight functions, which should determine the

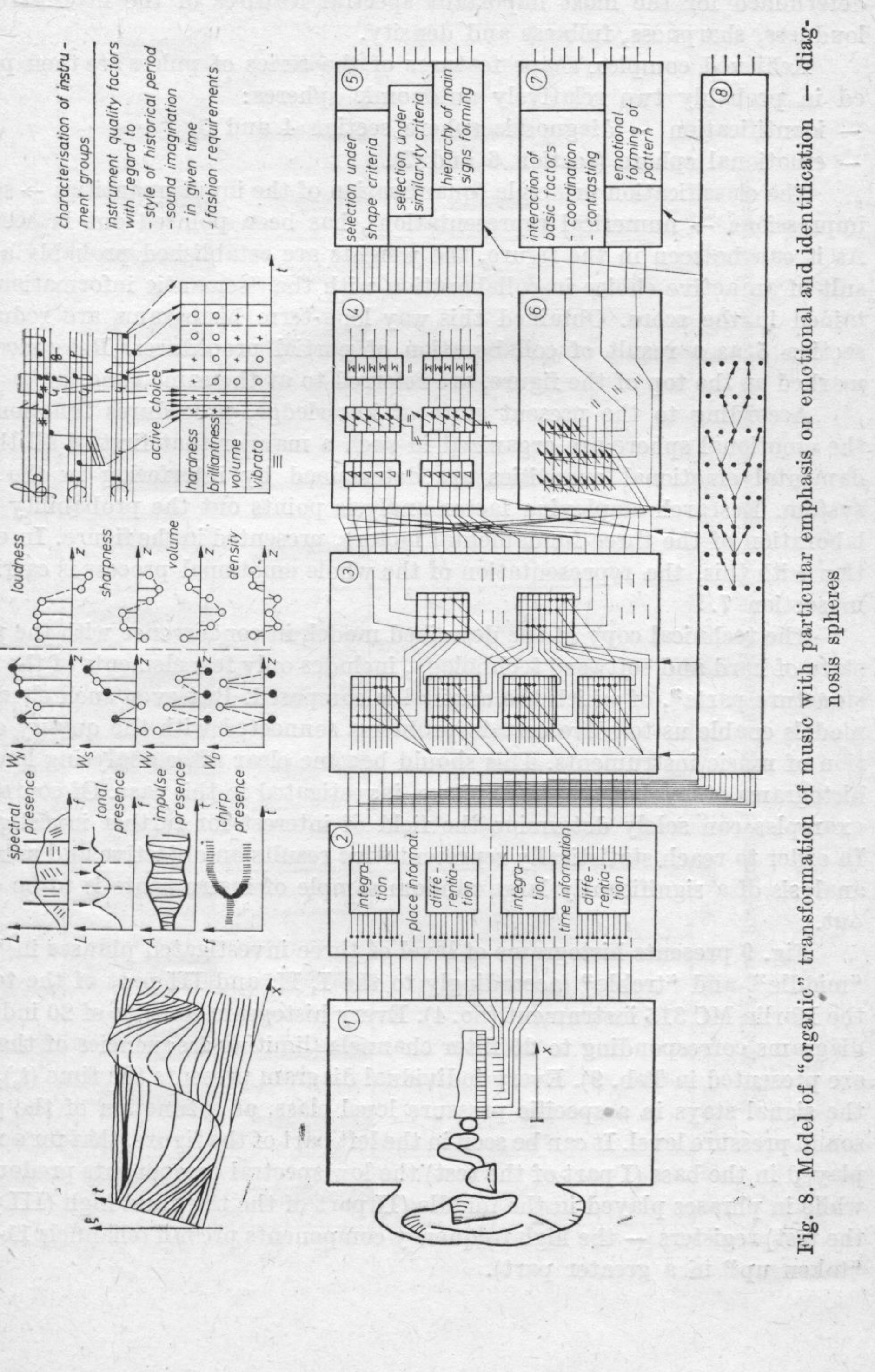

Fig. 8. Model of "organic" transformation of music with particular emphasis on emotional and identification — diagnosis spheres

various degree of dependence on the fundamental frequency of sound, can be determined for the most important spectral features of the macrostructure: loudness, sharpness, fullness and density.

Achieved complex shape features of the series of pulses are then processed in probably two relatively autonomic spheres:
— identification — diagnostic sphere section 4 and 5,
— emotional sphere (section 6 and 7).

The classification principle (quantization of the input quantities → sensoric impressions → numerical representation), has been pointed out in section 5. As it can be seen in the figure, the weights are established probably as a result of an active choice in collaboration with the "semantic information" contained in the score. Obtained this way long-term histograms are reduced in section 5 as a result of collaboration of partial procedures. Reference data, marked at the top of the figure, are referred to at the same time.

According to the present state of knowledge, procedures functioning in the emotional sphere are organized in such a manner that first of all the fundamental emotional quantities are determined by interfering in the limbic system. Research employing factor analysis points out the probability of collaboration of the three fundamental factors, presented in the figure. In connection with this, the representation of the whole emotional process is carried out in section 7.

The technical copy of the described model, in concurrence with the present state of hard and software technology, includes only few elements of the "lower structure parts", of which the original is composed. But even such elementary models enable us to solve certain problems connected with the quality evaluation of music instruments. This should become clear after analysing long-term histograms of level of the four guitars, investigated in this case. Of course these examples can solely determine the field of interest for further investigations. In order to reach statistically representative results an objective and subjective analysis of a significantly large random sample of instruments is to be carried out.

Fig. 9 presents histograms of level of three investigated phrases in "bass", "middle", and "treble" (accordingly to the I, II, and III part of the test) for the Marlin MC 315 instrument (no. 4). Every histogram consists of 20 individual diagrams corresponding to 20 filter channels (limiting frequencies of the filters are presented in Tab. 9). Every individual diagram presents the time (t_v), which the signal stays in a specific pressure level class, as a function of the general sound pressure level. It can be seen in the left part of the figure, that for a melody played in the bass (I part of the test) the low spectral components predominate, while in phrases played in the middle (II part of the test) and high (III part of the test) registers — the high frequency components prevail (channels 11–18 are "taken up" in a greater part).

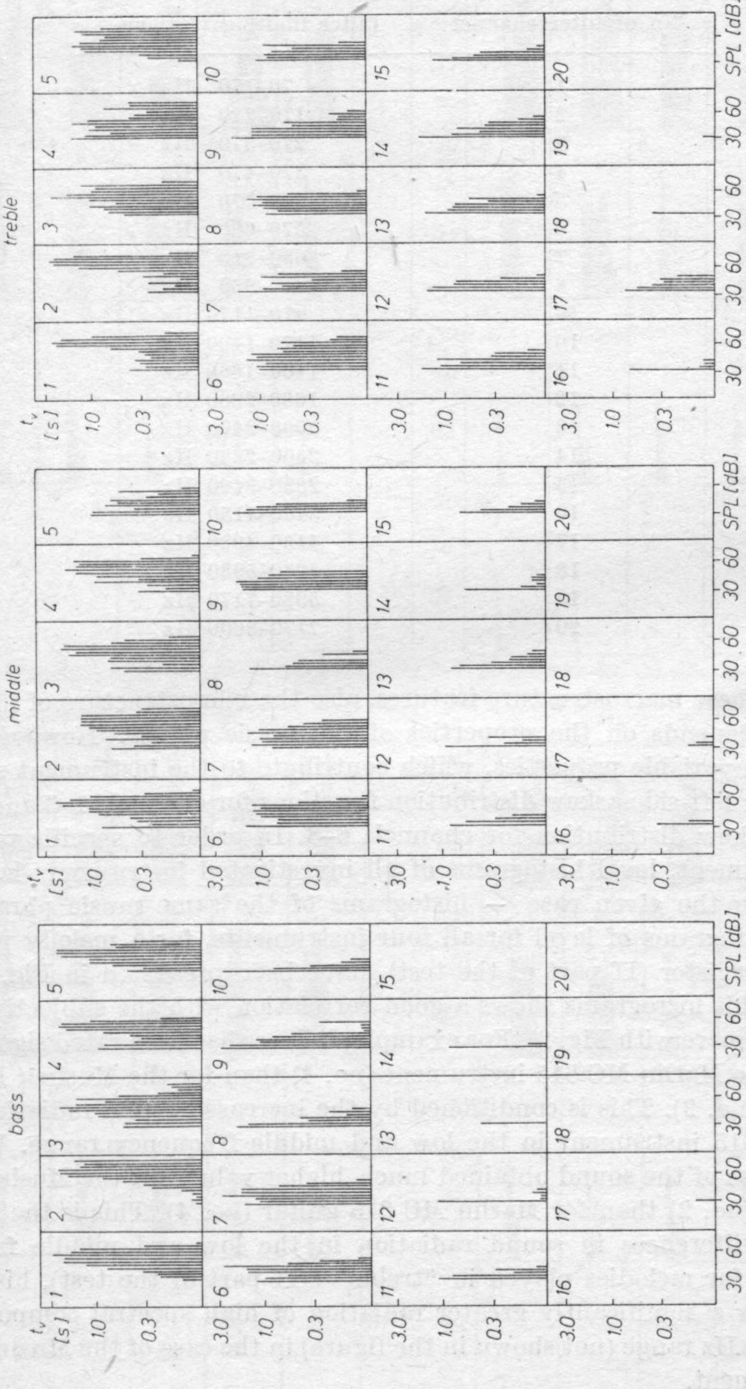

Fig. 9. ***SPL*** **level histograms for the Marlin MC 315 instrument for three investigated phrases**

Table 9. Limiting frequencies used in the computer

No of filter channel	Filter limiting frequency
1	70–170 Hz
2	170–270 Hz
3	270–370 Hz
4	370–470 Hz
5	470–570 Hz
6	570–680 Hz
7	680–810 Hz
8	810–970 Hz
9	970–1170 Hz
10	1170–1400 Hz
11	1400–1680 Hz
12	1680–2000 Hz
13	2000–2400 Hz
14	2400–2880 Hz
15	2880–3460 Hz
16	3460–4150 Hz
17	4150–4980 Hz
18	4980–5980 Hz
19	5980–7170 Hz
20	7170–8600 Hz

Beside these macrostructure features, also the microstructure of individual histograms depends on the properties of the music phrase. However, there are several invariable properties, which contribute to the instrument specifity, e.g. typically left-side askew distribution functions for channels 1–3 and a more right-side askew distribution for channels 6–8. In order to specific properties of the instrument, level histograms of all investigated instruments have been compared; in the given case — histograms of the same music phrases. For example, histograms of level for all four instruments, for a melody played in the middle register (II part of the test), have been presented in Fig. 10. The analysis of this histograms shows a good correlation with the subjective sound features (compare with Fig. 2). For example, fullness has been rated significantly higher for the Marlin MC 315 instrument (no. 4) than for the Musima Resonata instrument (no. 2). This is conditioned by the increased sound radiation of the Marlin MC 315 instrument in the low and middle frequency range. Whereas, the brightness of the sound obtained much higher values for the Musima Resonata guitar (no. 2) than for Marlin MC 315 guitar (no. 4). This is the result of mentioned differences in sound radiation in the low and middle frequency range. Also, for melodies played in "treble" (III part of the test), histograms of level show a significantly greater radiation of high spectral components in the 1.7 — 4 kHz range (not shown in the figure) in the case of the Musima Resonata instrument.

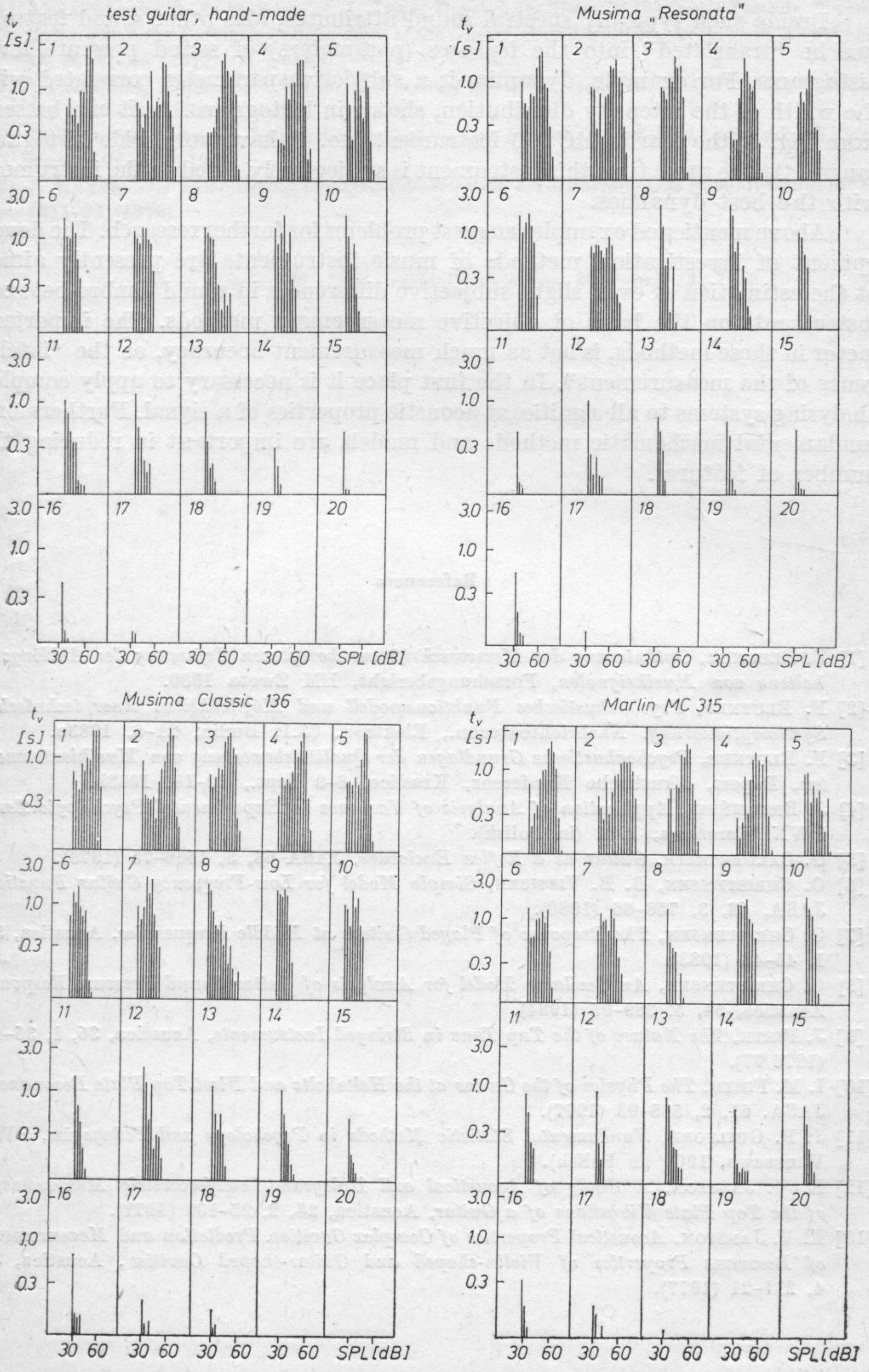

Fig. 10. ***SPL*** **level histograms for four investigated instruments for the melody performed in the middle register**

Beside such typically spectral sound attributes, also other sound features can be "translated" into the features (parameters) of sound pressure level histograms. For example, dynamics is a subjective parameter correlated with the width of the intensity distribution, shown in histograms. As it can be seen from Fig. 6, the Marlin MC 315 instrument (no. 4) have very wide histogram ranges. At the same time this instrument is subjectively rated as the instrument with the best dynamics.

Above mentioned examples suggest problems for further research. The development of investigation methods of music instruments are presently aimed at the estimation of even slight subjective differences in sound timbre between instruments on the basis of objective measurement methods. The important factor in these methods, is not as much measurement accuracy, as the "intelligence of the measurement". In the first place it is necessary to apply complex analysing systems to all significant acoustic properties of a signal. Furthermore, fundamental mathematic methods and models are important in reducing the number of features.

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