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13. THE ACOUSTIC ANALYSIS OF VIOLINS AND THE ARTISTIC IMPRESSIONS EVALUATED BY MUSICIANS

Mariana Domnica Stanciu,[39] Alina Maria Nauncef,[40] Florin Dinulică,[41] Mircea Mihălcică,[42] Vasile Ghiorghe Gliga,[43] Silviu Marian Nastac,[44]

Abstract: *Violin studies can be classified into two main types: psychoacoustic studies, which are based on the artistic perception of audibility by violinists and vibro-acoustic studies, which are based on the spectral analysis of the vibrations and sounds produced by the instruments. The paper presents the acoustic analysis of violins by means of specialized software, their main acoustic characteristics being extracted in the form of frequency spectrum, spectrograms, specific modes and number of harmonics. These results were compared with the results of the opinion poll among musicians regarding the acoustic qualities of violins, based on musical auditions. The results highlighted the fact that the acoustic analysis technique cannot detect in totality the psycho-acoustic effects of musical sounds, therefore the establishment of the acoustic quality of the instruments on objective foundations, since the personal touch of an instrumental artist aims at the approach and articulation of the musical discourse, in a complex manner, combined with the interpretation of forms and styles.*
Key words: *spectral analysis, violin, psycho-acoustic effects, violin*

1. Introduction

In an attempt to discover what exactly determines the crystalline and smooth but also brilliant sound of the violins of the Italian luthiers, a lot of research was done on all the aspects related to the quality and age of the wood, the varnish, the exact measurements of all the components of the violin [1-5]. But what exactly is a violinist looking for when he wants to buy a violin? Apart from shape, colour and size, an instrument player is looking for a certain sound to suit his personal requirements. This aspect leads to some subjectivity in evaluating the quality of a violin. There are violinists who are looking for a less powerful instrument, but with a warmer and less bright sound, suitable for example to play in an ensemble: small chamber ensembles, chamber orchestras, symphony orchestras, etc. The great soloists and violinists who are very active on concert stages are looking for an instrument with a brilliant sound, which penetrates any kind of hall (small or very large), but does not compromise on the quality of this sound, which must also have warmth and "roundness", with harmonics and a lot of finesse.

All these characteristics sought and appreciated by violinists are part of the violin's personality, which is characterized by its acoustic timbre. According to [6] timbre is "more than a characteristic of sound: it is sound itself, one of the

39 Associate Professor PhD., Engineer, ”Transilvania” University from Brașov, România, email: mariana.stanciu@unitbv.ro
40 Associate Professor PhD., ”Transilvania” University from Brașov, România
41 Professor PhD., Engineer, ”Transilvania” University from Brașov, România
42 Associate Professor PhD., Engineer, ”Transilvania” University from Brașov, România
43 Engineer, Candidate Doctoral, ”Transilvania” University from Brașov, S.C. Gliga Instrumente Muzicale S.A. from Reghin, România
44 Professor PhD., Engineer, ”Transilvania” University from Brașov, "Dunărea de Jos” University from Galați, România

fundamental attributes of musical expression". The timbre consists of the number and intensity of the harmonics, and the factors that influence the timbre are: the number of harmonics; the position of the harmonics in their series; the intensity of the harmonics; the position of the foundation on the height scale; fundamental intensity; the noise factor that accompanies musical sound. On the other hand, the musical timbre is determined by numerous physical factors, whose combinatorial variety creates the quasi-infinity of timbres encountered in practice [6] and hence the difficulty of detecting the acoustic quality of a violin or the so different preferences of violinists.

From the studies carried out by [7-12], correlations were established between linguistic terms describing the acoustic timbre elaborated in English for native English speakers, the perceptual difference between these terms and the acoustic properties of violins. The method consisted of grouping the terms into semantic sets, resulting in a large number of combinations, the method being improved so that it could be interpreted from a statistical point of view. Among the acoustic descriptors of the timbre of violins, highlighted in works [9-15], can be mentioned: dynamic (alive), balanced, crazy (brash), bright, sparkling (brilliant), clean; clear, closed, cold, complex, inert (dead), dark, deep, boring (dull), free, full, heavy (hard), harsh (rough), hard, light, jolly (lively), loud, mellow, metallic, muffled, nasal, not penetrating, open, penetrating, sharp (piercing), powerful, pure, quiet, hoarse (raspy), resonant, receptive, rich, rough, round, sharp, strident (shrill), smooth, light (soft), sonorous, steely, strident, strong, sweet, unbalanced, uneven, unresponsive, warm, weak. The objective of the study was to analyse the acoustic signals recorded on violins belonging to different classes of acoustic quality, both objectively (acoustic analysis) and subjectively (psychoacoustic impressions).

2.2. Materials and method

2.1. Studied violins

The studied violins were characterized by different thicknesses of the top and back plates (some had plates reduced by 0.2; 0.4; 0.6 mm, others had plates thicker by 0.2; 0.4; 0.6 mm, compared to the nominal thicknesses). Demonstration violin types in number of 56 violins, taken in the study as presented in Table 1, were built by the factory of musical instruments S.C. Gliga Instrumente Muzicale S.A. The coding of violins is based on the following principle: the first letter represents the anatomical quality class of wood (A, B, C, D), the following code represents the type of thickness (0 - nominal thickness used in the current production of violins; P - increased thickness; M - reduced nominal thickness); the figures represent the tenths with which the nominal thickness has changed (2; 4; 6 - represents the quantity 0.2; 0.4; 0.6 mm which was reduced or added to the nominal thickness). Since varnishes influence the acoustic quality of the violins, and depending on the quality class, oil-based or spirit-based varnishes are used, in this stage, violins were recorded in white, i.e. unvarnished.

Table 1: Types of studied violins

Types	Violins codes						
Maestro A	AM6C1	AM4C1	AM2C1	A00C1	AP2C1	AP4C1	AP6C1
Maestro A	AM6C2	AM4C2	AM2C2	A00C2	AP2C2	AP4C2	AP6C2
Professional B	BM6C1	BM4C1	BM2C1	B00C1	BP2C1	BP4C1	BP6C1

Professional B	BM6C2	BM4C2	BM2C2	B00C2	BP2C2	BP4C2	BP6C2
Student C	CM6C1	CM4C1	CM2C1	C00C1	CP2C1	CP4C1	CP6C1
Student C	CM6C2	CM4C2	CM2C2	C00C2	CP2C2	CP4C2	CP6C2
Școlar D	DM6C1	DM4C1	DM2C1	D00C1	DP2C1	DP4C1	DP6C1
Școlar D	DM6C2	DM4C2	DM2C2	D00C2	DP2C2	DP4C2	DP6C2

2.2. The methods

2.2.1. Acoustic analysis

The acoustic analysis of violins consisted of recording and processing the acoustic signals emitted during the musical performance of violins belonging to different quality classes A (maestro), B (professional), C (student) and D (school). All the violins studied were equipped with the same types of strings so that the acoustic signal is not influenced by the quality of the different strings. To produce the sounds, the same bow was used throughout the experiment, and the interpretation of the musical fragments was performed by the same violinist. The musical fragments chosen for testing the violins consisted of three parts, the total duration of the emitted signals being approximately 1 minute, the details of the musical sequences being presented in the previous study [16, 17]. In advance, all violins were tuned and prepared for recordings.

The signals were recorded in a ".wav" audio file format. The specific recording parameters were: 24 bits per sample, 48 kHz sample rate, uncompressed. The post-processing and analysis of the recorded signals were performed in the mathematical platform Matlab, using specific developed applications for scaling, cutting the signal on significant domains, Fast-Fourier-Transform (FFT) and Short-Time-Fourier-Transform (STFT) processing and stochastic analyses. In the signal processing, the specific frequencies of the free strings were assimilated with the notations in the music to make the information accessible to everyone. Thus, the 196 Hz G chord is known as the G# string; the D string (293.7 Hz) is equated to the literary symbolization D#; the A string (440 Hz) known as the A# string; and the E string (659.3 Hz), with the symbol E# [18].

The recorded and processed musical signals by domains of interest are shown in

Fig. 1. In these figure, the dynamics of sounds characterized by transient phenomena (the attack period and the extinction period of the sound emission), the continuous variation of the sound emission [6, 17] can be observed. The transient processes of musical sounds have two stages (initial and final) - the first stage is that of the "sound attack", the stage in which it goes from the state of rest to the state of vibration, the intensity of the sound gradually increasing up to the desired value, and in the second stage, of extinction, is the attenuation of the sound, the intensity gradually decreasing to zero. Between the two stages, sound stabilization occurs, this being a stationary process, when harmonics and other phenomena related to acoustic emission and interpretative techniques intervene [6, 17].

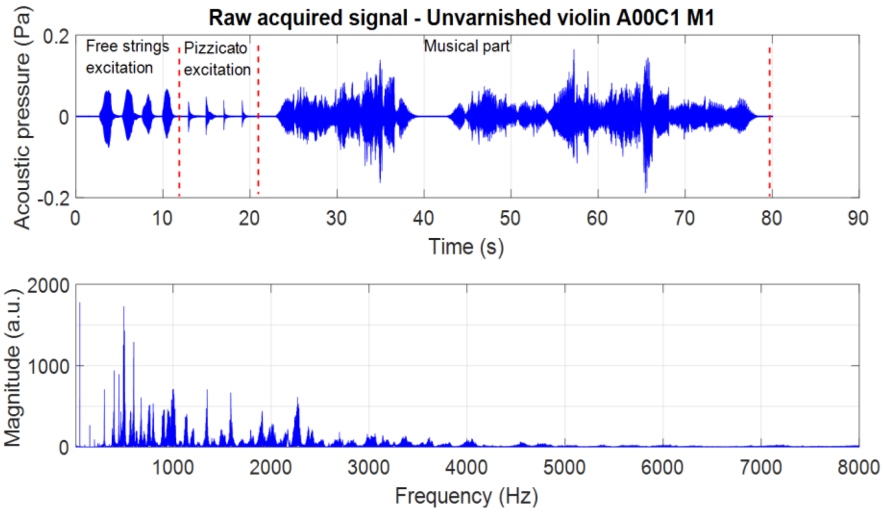


Fig. 1. Time analysis of recorded signals

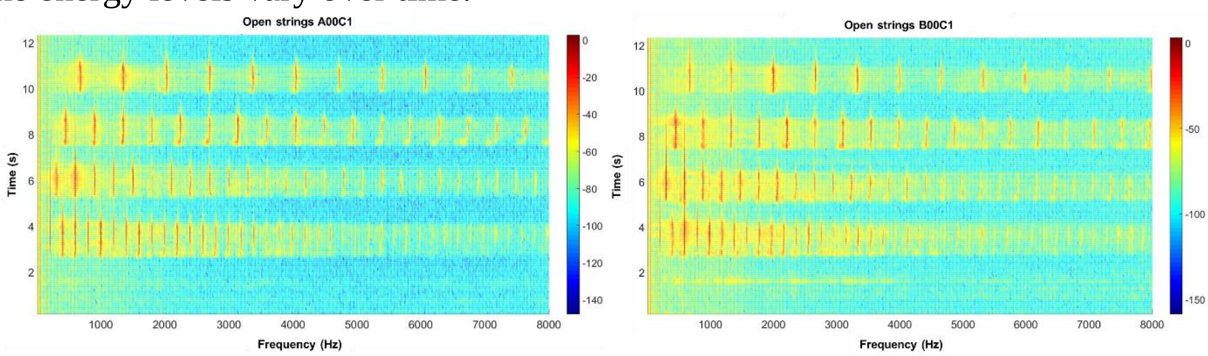
2.2.2. The acoustic quality evaluation survey

The psycho-acoustic analysis was based on the procedure presented in previous publications [16–18], in the present study the sample of evaluated violins was extended. After listening to the recorded musical sequence, the respondents assigned for each violin heard, notes from 1 (poor) to 5 (excellent), corresponding to the acoustic quality criteria: bright and strong tone; sound clarity; warm sound; amplitude of sounds; equal sound on all 4 strings. In the first stage, for each noted parameter and each violin, the average of the scores given by the respondents was calculated, obtaining a ranking from the point of view of audience experience, gender, age, but also for each violin and acoustic criterion evaluated. Then, in order to achieve the ranking regarding the acoustic quality of the violins, the averages obtained by each individual violin in relation to each acoustic criterion were comparatively analyzed.

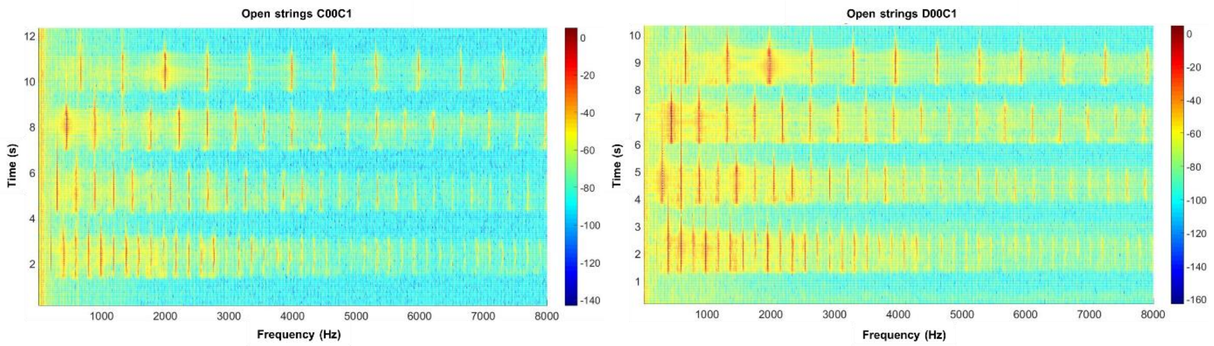
3. Results and Discussions

3.1. Post-processing of acoustic signals

Fig. 2 shows the spectrograms obtained for the reference violins, from the four quality classes. Thus, the signal strength or signal "intensity" over time can be observed. Visually, signal intensity is correlated with the hues and intensity of colors at different frequencies present in a given waveform. Not only can one see if there is more or less energy depending on the emitted frequency, but one can also see how the energy levels vary over time.



a) b)



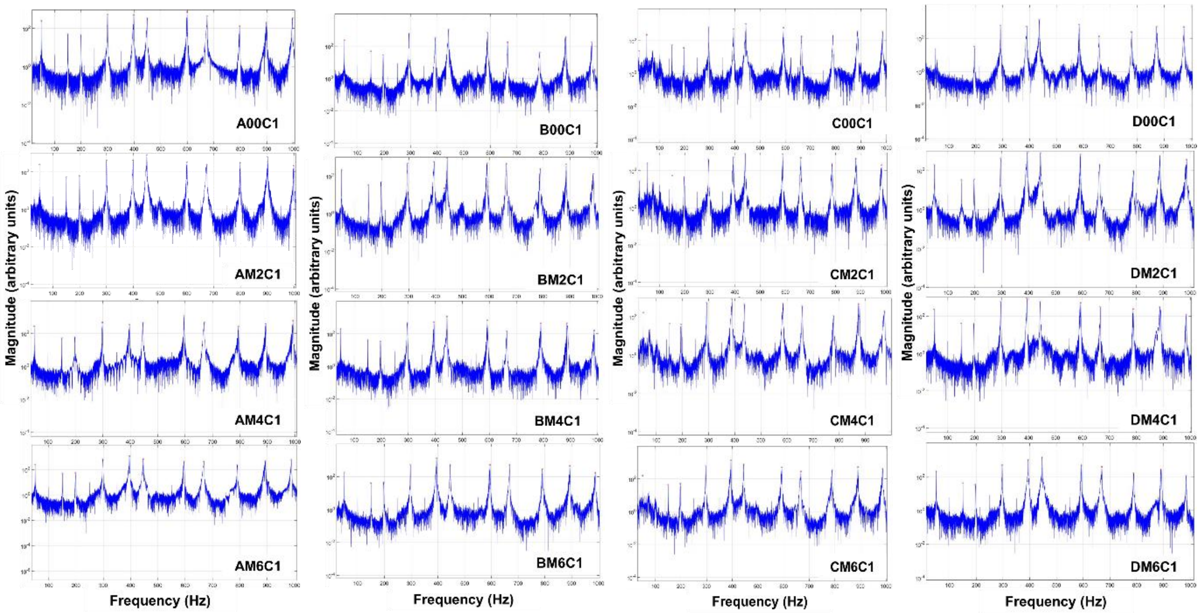
c) d)

Fig. 2. The spectrograms for the signal obtained by exciting the strings: a) maestro violin (A00C1); b) professional violin (B00C1); c) student violin (C00C1); d) school violin (D00C1)

A spectrogram is a detailed visualization of sound, capable of representing time, frequency and amplitude on a single graph, which allows for quick sensing through visual analysis of the graph, of the acoustic evolution of the signal. In the spectrograms shown in Fig. 2, the frequency is represented on the abscissa, the time on the ordinate, and the intensity of the signal through the color spectrum. It can be seen that each spectrogram consists of four bands corresponding to the signal emitted by each individual string. Thus, the response of the analyzed violins differs according to the characteristics of the resonance body. The correlation between spectrograms and clear, bright sound is given by the clear distinction of frequencies (harmonics). The lower midrange as well as the upper section of the bass range are important because they contain the fundamental frequency of many acoustic instruments.

The lower midrange of music is around the 250-500 Hz frequency range. The fundamental frequency of the sound is the frequency that determines the pitch of the sound. It is almost always the strongest frequency in a sound. When this range is not heard accurately, the instrument sounds unnatural, unclear. The next frequency range is the center range or midrange, an important range in the range of 500-2000 Hz. This range is in a range beyond the fundamental frequency and harmonics or lower tones, adding clarity and detail. Excessive amplification of sounds in the 1 kHz range can result in a "horn"-like acoustic effect or the sound having a metallic quality [6, 17].

The upper midrange is the 2-4kHz range, where adequate clarity is needed. Due to the shape of the human ear, the ear canal (the section that goes from the outer ear to the eardrum) naturally resonates in a range of about 3.5 kHz [6, 17]. Figure 3 shows the frequency spectra of the studied violins, using as a reference spectrum the spectrum of violins with nominal factory thicknesses of the same quality class. To visualize the shape of the frequency spectrum, the range 50-1000 Hz was chosen, being related to the range specific to the vibration modes of the violin body [17 - 18].



a) b) c) d)

Fig. 3. The FFT analysis: a) maestro violin (A00C1); b) professional violin (B00C1); c) student violin (C00C1); d) school violin (D00C1)

As can be seen, due to the resonant body of violins, each partial tone corresponds to an ensemble of continuous neighboring frequencies covering a band of frequencies. Of these frequencies, the one with the maximum amplitude (maximum intensity) is the frequency of maximum resonance. According to [6], the width of the resonator frequency bands is determined by the properties of the oscillating material (its mass and elasticity), in this case - the strings, as well as the physical-geometrical properties of the resonating body. This aspect explains the beauty of musical sounds given by the way the vibrational energy is discharged, it is distributed over a greater or lesser number of frequencies that form a continuous band, depending on the mode of attack of the note. According to the specialized literature, the acoustic analysis technique cannot fully detect the psycho-acoustic effects of musical sounds, so establish the acoustic quality of the instruments on objective foundations, since the personal touch of an instrumental artist is aimed at the approach and articulation of the musical discourse, in a complex manner, combined with the interpretation of forms and styles [6].

The octave analysis consisted of applying a set of filters, each filter having a center frequency and a bandwidth. Thus, analysis was used in a single octave band (noted 1/1) and in thirds of an octave (1/3). The central (nominal) frequencies of the frequently used octaves were: 22.1 Hz; 44.2 Hz; 88.4 Hz; 176.8 Hz; 353.6 Hz; 707.1 Hz; 1414.2 Hz; 2828.4 Hz; 5656.9 Hz; 11313.7 Hz; 22627.4 Hz, the central frequencies covering an octave (one is double the other) [17, 19]. In Table 2 are centralized the total number of resonance and harmonic frequencies in the frequency spectrum of the musical part. The BM6C2 violin registers the lowest number of harmonics (168), and the maximum is reached by the CP4C2 violin. In order to achieve a ranking of the violins from the point of view of the harmonic spectrum, the minimum and maximum values were identified, the difference was calculated and divided by 5 (the intervals also used in the artistic impression questionnaires). Then the intervals were established, and the violins whose number of harmonics was found in a certain interval were evaluated with a number from 1 to 5, where 1 corresponds to the minimum values, and 5 to the maximum values.

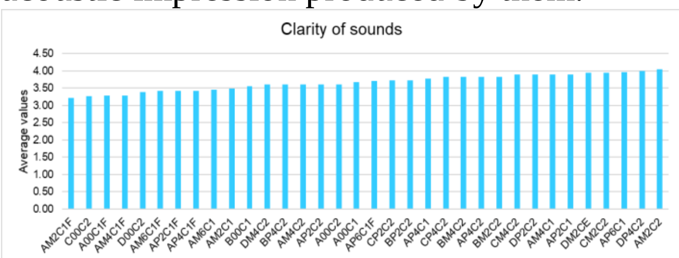
Table 2: The score of violins according to the number of harmonics

Types	M6	M4	M2	00	P2	P4	P6
A	2	4	4	4	4	4	5
	5	4	3	2	5	3	4
B	1	3	1	2	2	3	2
	2	1	2	3	3	4	2
C	4	4	4	4	5	5	4
	2	3	4	3	1	4	4
D	3	3	2	4	3	3	3
	1	2	4	4	2	4	4

3.2. Evaluation of acoustic quality by the audience

The psycho-acoustic analysis revealed the respondents' preferences regarding the acoustic quality of the sounds emitted by the tested violins, in relation to the established quality criteria (Fig. 4). Thus, it turned out that from the point of view of "clarity of sounds", the highest scores (with an average of 4) are given to AM2C2 violins; DP4C2; AP6C1. The lowest scores, also from the perspective of sound clarity, but above average (over 2.5 of the maximum value 5) are obtained by the AM2C1F violins; C00C2; A00C1F; AM4C1F (score range 3.23-3.29) (Fig. 4, a). From the point of view of "warm sound", the highest score is obtained by the DP4C2 violin (score 4.17), and the lowest scores are for the A00C1F violins (score 3); D00C2; AM6C1F; AP2C1F; AM6C1 (score range 3.23-3.29) (Fig. 4, b). The "bright tone" is most appreciated in the CM2C2 violins; AM2C2 (score range 4.00-4.17), and the least appreciated, for AM4C1F violins, A00C1F (scores below 3) (Fig. 4, c). The "amplitude of sounds" rating revealed a maximum average of 4 for the CM4C2 violin, with close scores being the CM2C2, BM2C2, CP4C2 violins.

The lowest score was obtained for the AM4CF violin (Fig. 4, d). For the criterion "Equal sonority on all strings", the maximum score obtained on the samples heard is 4.17 for the DP4C2, BM2C2, DM2C2, BM4C2 violins. The lowest score was obtained for the AM4C1F and AM6C1F violins (Fig. 4, e). The ranking of psycho-acoustically tested violins is shown in Fig. 5 where it can be seen that all the violins obtained a general score above the average, with the following violins ranking first: DP4C2; CM2C2; AM2C2; BM4C2; CP4C2; CM4C2; AP6C1; DP2C2; BM2C2 (score 19.00 – 20.00). It is found that increasing or decreasing the thickness by 0.2-0.6 mm can lead to an improvement in the acoustics of violins, compared to the reference model practiced in the factory, the thickness variation taking into account the density of the material and less the regularity of the anatomical structure of the wood. It should be noted that in the psycho-acoustic evaluation, the respondents viewed the instrument, so the scores given are based exclusively on the acoustic impression produced by them.



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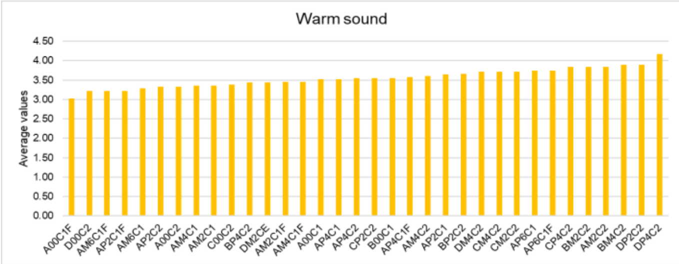

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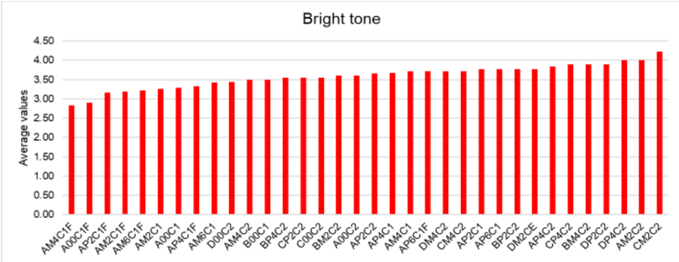

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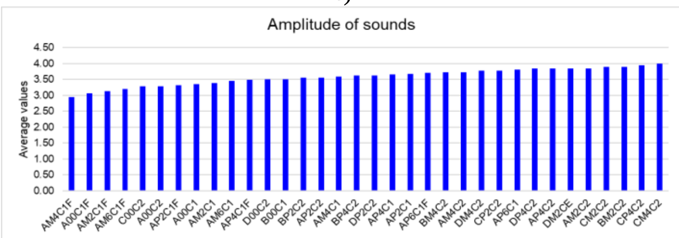

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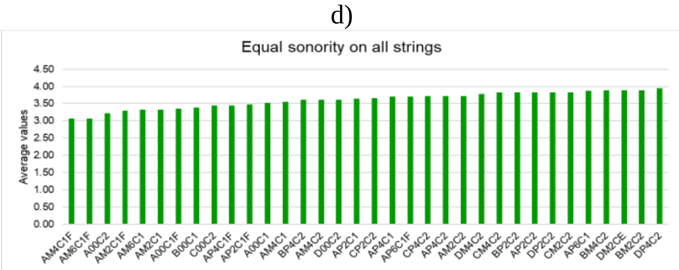

e)

Fig. 4. Stratification of violins according to the psycho-acoustic preferences of the respondents: a) sound clarity; b) warm sound; c) bright tone; d) amplitude of sounds; e) equal sonority on all strings

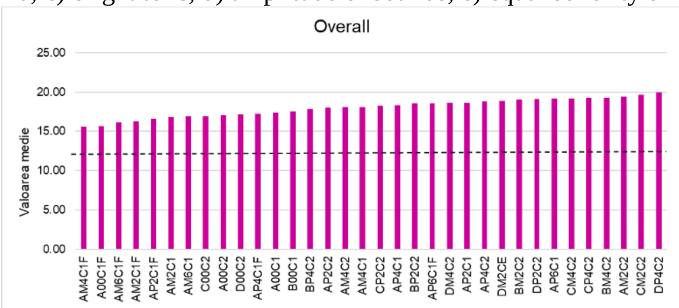

Fig. 5. The classification of violins from a psycho-acoustic point of view

3.3. Correlations between acoustic analysis and psychoacoustic assessment

For luthiers, it is important to correlate the artistic impressions of the violinists with the geometric and material parameters of the produced violins. Thus, the statistical links between the results of the acoustic analysis of the signals and the artistic impressions quantified in the scores given by the respondents to the musical samples performed on the studied violins were investigated. It was found that there are a number of factors that influence the assessment of the acoustic quality of violins (age, experience, gender and the position of the musical sample in the questionnaire).

The variables that significantly influenced ($p \leq 0.05$) the respondents' scores for sound clarity are only their gender and experience. Respondents with more musical experience (especially those with more than 26 years of experience) were more demanding in their assessment of sound clarity and provided the widest range of scores in assessing this quality. The overall contribution of the explanatory variables reported to the variations of the global scores is only 15%. The only determinants of the overall scores are, in descending order of significance: the respondents' experience, their gender, and the vibration frequencies of the free strings. Respondents with more musical experience and women gave lower scores than the other categories of respondents. The relationship between experience, frequency modality and total score is plotted in Fig. 6 [20].

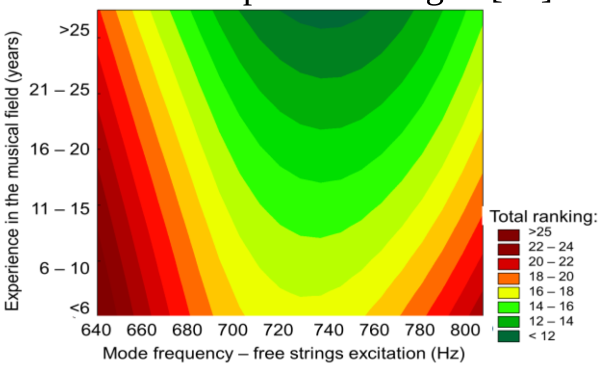

Fig. 6. The correlations between musical experience – free string frequency modulus and respondents' overall

4. Conclusions

The correlation of the artistic impressions with the acoustic analysis, led to the following conclusions:

- Violins that recorded resonance frequencies of 295 - 298 Hz and 596 Hz were perceived as having a clear sound, with amplitude and equality on all strings.
- Violins with a frequency of 396 Hz in the spectrum of harmonics were perceived by respondents as having a clear and equal sound on all strings, with amplitude, brightness and warmth;
- Violins whose B1 mode frequencies are in the range of 444–448 Hz were also rated for their clear and equal sound across all strings, amplitude and brightness.
- The dominant frequency evident in the highest scores for most criteria assigned by artists was around 450 Hz. The most frequent harmonic perceived by respondents was around 670 Hz, followed by 665 Hz.
- For the Pizzicato style, the clarity of the sound and the brightness were given by the frequency of 665 Hz emitted by the violins, a value that is also found in the case of exciting the free strings with the bow.
- For the musical sequence analysed, the violins that emitted sounds around the frequency of 1800 Hz were rated as having the warmest sound and bright, equal amplitude on all strings. The frequency of 2800 Hz comes close to the acoustic quality in respondents' preferences, but only for clarity and brightness of sounds.

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