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THE EFFECT OF BOWING TECHNIQUE ON VIOLIN SOUND

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Abstract: By the bowing of a violin especially by folk and gipsy bands a special bowing technique can be observed. Often a diagonal (not perpendicular to the string) bowing, resp. the bow slids onto the fingerboard. This study deals with the effect of this special bowing technique on the emitted sound of a violin and compares it with the classic detaché bowing technique on all four strings.

Keywords: *bowing technique, sound measurement, Total Harmonic Distortion, inharmonicity, frequency spectrum, sharpness, roughness*

1. INTRODUCTION, MOTIVATION

Watching folk bands play, it is obvious that the violin has a leading role in their playing. Therefore, the attention is directed to the violinist – let he/she be the lead or the soloist. There is a large amount of literature on correct bowing techniques. The main thing is, among other things, that the bow should run between the bridge and the fingerboard, perpendicular to the strings as shown in Figure 1, which was recorded at real performances.

Figure 1. *Analysing methods of fatigue behaviour*

Having listened to and observed several performances by folk bands and gypsy bands, the violinist and the viola players who played the accompanying parts, this method of conducting the bow was different. Mostly the location of the bow was not perpendicular or nearly perpendicular to the strings, but inclined and slid onto the fingerboard (sul tatso) as this can also be seen in Figure2.

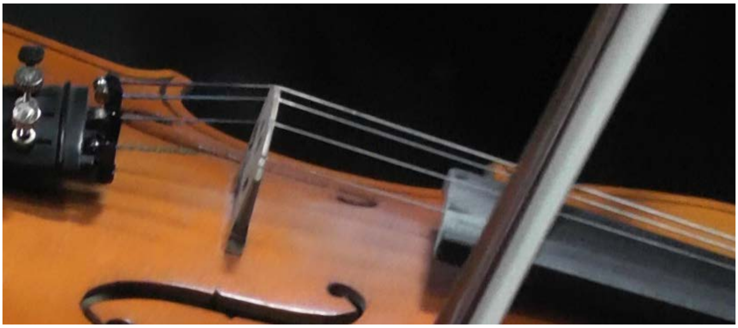


Figure 2. *Bowing on the fingerboard (sul tasto)*

Perhaps it is not by chance that among the first fiddlers of a gipsy band who graduated from the College of Music or University, bowing was much more disciplined. These observations encouraged us to carry out the following tests, namely whether the oblique bowing or a possibly string sliding to the end of the fingerboard, causes a tonal difference.

In general, several other investigations were performed by other authors regarding to the classification of violin sound, among others the classification of bowing techniques too. Alar et al (Alar, Mamaril, Villegas, & Cabarrubias, 2021) investigated five types of bowing techniques, detaché, double stops, Ricochet, legato, spiccato and they introduced a model based on a convolutional neural network which determines the played sound and classifies it. The proposed model can help new violin players to understand each technique better.

Maestre et al (Maestre, Blaauw, Bonada, Guaus, & Perez, 2010) investigated bowing control techniques, how could they be applied to artificial violin sound synthesis. They included to the work different bowing parameters, like the temporal contour of bow velocity, bow pressing force, and bow-bridge distance. With the help of considering these parameters in the synthesis synthetic contours could be generated through a bow planning algorithm.

Su et al (Su, Lin, & Yang, 2014) studied several violins and collected 33 bowed single tone samples. They used new approach, instead of state-of the art time and frequency domain methods, they extracted from the magnitude spectra and phase derivatives, including group delay function (GDF) and instantaneous frequency deviation (IFD). This approach led to significantly better performance of understanding bowing techniques.

Wang et al (Wang, Lostanlen, & Lagrange, 2023) studied also convolutional neural network in the time–frequency domain and investigated the classification of five comparable real-world playing techniques from 30 instruments spanning seven octaves. They found that relevant regions around the modulation rates of the playing techniques regardless of the pitch could be localized which are highly relevant to the technique.

We can state that the diagonal bowed technique was not investigated and compared with other ones until now, so this highlights also our intention for the investigations.

2. THE ROLE OF THE VIOLIN IN MUSIC

If we want to highlight the importance of the violin in one word, we can only say that it is indispensable, it should be featured as a solo instrument, e.g. J. S. Bach, N. Paganini, and its orchestral literature is endless. With this instrument you can express every feeling of life. It is no coincidence that a whole series of excellent violinists could be listed. The orchestral role of the instrument cannot be avoided, it has a prominent role, perhaps it is no coincidence that they are located on the left side of the conductor's heart.

3. DESIGN OF THE VIOLIN AND THE WAYS OF MAKING IT SOUND

The violin is the highest-tuned and smallest member of the violin family of stringed instruments, with strings pitched 4 fifths apart (G-D-A-E). The group also includes the bass violin, or more commonly known as the viola, the cello and the double bass The lowest string (which is the lowest note that can be played on the violin) is the minor G, followed by the single-line D, single-line A, or two-line E strings. Violin scores are written in treble clef (also known as G-clef). The structure and parts of the violin are shown in Figure 3.

The strings alone are not enough to hear the usual sound from the violin. A violin sound is obtained if the instrument has a designed body (cavity resonator), which amplifies the overtones and determines the direction of the radiation too. The string and body are usually rigidly connected but can also be air-coupled. The important part, the so called "soul", is not fixed by glue to the body of the violin it is only clamped inside between back and front side of the violin. Its placement is crucial for the timbre. If there would not be a soul inside, the violin will sound like a guitar when bowed.

In addition, the tailpiece performs the coupling between the vibration of the string and the vibration of the body. The purpose of the tailpiece is to take as much energy from the string and transfer it to the body so that the radiation remains uniform. But there should be enough energy left on the string so that with a constant bow, the constant vibration remains on it. In the best case, with a small violin, even with a little effort, you can play a sound equivalent to the volume of an entire orchestra! (This "small" energy investment means that with 1% efficiency, 99% is converted into heat; but to achieve the same volume, the opera singer does ten times as much work).

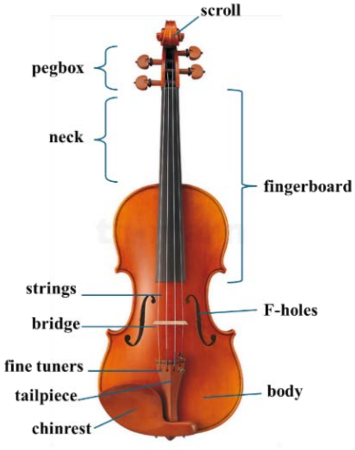


Figure 3. *Cantilever Beam*

With strings, it is difficult to control the timbre, which results from the sawtooth-like excitation of the string. By increasing the bowing speed, the vibration amplitude (and volume) of the string can be increased. By increasing the bowing force (bow pressure), only the timbre (vibration shape of the string) can be influenced, not the intensity. Pulling the string close to the foot also requires a larger bowing force. Under a minimum bowing force, no musical sound is produced. To bow a thicker string, more force (pressure) is required, therefore instruments with thicker strings have a shorter bow.

The bowing force changes the intensity distribution of the overtones, a higher force emphasizes higher overtones and suppresses lower ones - without changing the overall energy, so the musician may mistakenly perceive that he has (also) increased the intensity with the bowing force, but only he perceives this, the audience no longer.

According to the Hornbostel-Sachs classification, the violin has the identification number 321.322-71. The first three numbers show that it belongs to the family of chordophones (3), compound chordophones (32) and lutes (321). Another three numbers refer to the construction of the violin, i.e. lute with handle (321.3), neck lute (321.32), or box-tie (321.322). The last two digits of the Hornbostel-Sachs classification refer to the method to cause the strings to vibrate: by bowing (321.322–7) and using bow (321.322–71).

From the point of view of the present study, these two latter are important, since our goal is to present the effect of a certain way of string bowing technique on the created acoustic experience. In accordance with these, the violin strings were bowed in several ways: with normal and high pressure, as well as by pulling the string diagonal (oblique).

4. THE PHYSICS OF VIOLIN SOUND

Being a chordophone (stringed) instrument, the basic tone of the violin is produced by making the strings to vibrate. Strings are elastic fibres that have negligible diameter compared to their length, clamped and stretched at both ends, and can vibrate in three ways: transversal, longitudinal and torsional. The main mode of vibration is transverse, and when excited, the string performs several different vibrations, the frequencies of which are given by Mersenne's law in Equation 1 (Beyer, 1999).

$$f = \frac{n}{2L}\sqrt{\frac{F}{Aq}} \tag{1}$$

where n represents a series of integers (n=1,2,3 ...), L is the length of the string, F is the tension force, A is the cross-sectional area of the string and ρ is the density of the string material. The amplitude, starting phases and timbre of the individual natural vibrations are also determined by the initial state (shape and speed) of the string. Depending, for example, on where a string is bowed (between the two clamped ends at the halfway point, at the third, at the fifth), the given harmonics and their integer multiples may be missing from the spectrum (Figure 4).

Of course, the violin is typically not played by picking, however, the presence of individual harmonics in the spectrum is similar when playing with a bow. The aim of our study is therefore to be able to make a measurable difference between violin sounds played with different bowing techniques. For this, we perform measurements and evaluate the measurement results using different methods, and then select the method that seems most suitable for comparing the quality of violin sounds.

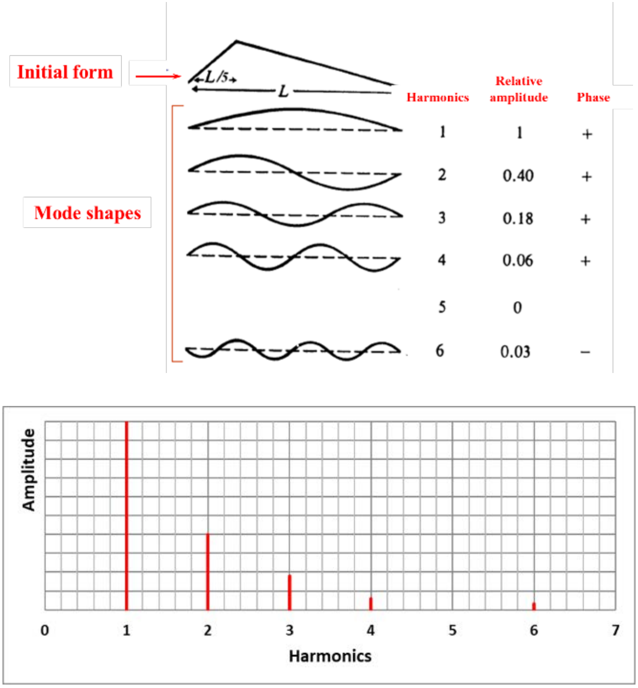


Figure 4. *Vibrations and theoretical spectrum of a string picked at the fifth of the length*

5. STRUCTURE AND EXECUTION OF THE MEASUREMENT

The string treatment methods can be compared in the simplest way if the violin strings (A, D, E, G) are bowed with the desired bowing technique, and the sounds emitted at that time are recorded, then the recorded sounds are subjected to acoustic analyses and the results are compared.

To make the recordings, we used a room that is free from disturbing reflections, and the external disturbing noises do not enter the room either. For this purpose, the (semi-) anechoic chamber of the Institute of Machine and Product Design of the University of Miskolc proved to be the most suitable. The four walls and the ceiling of the measuring room (except for the spy window) are covered with material that absorbs sound waves. The floor is covered with sheet steel. With this arrangement, e.g. we can also determine the sound power of machines and equipment based on the relevant standards (e.g. EN ISO 3741).

To record the sound, we placed 2 pieces B&K 4189 type free field microphones in 15 cm distance, approx. at 1 m distance from the violin, and 1.2 m distance from the floor. We did not consider it necessary to use a wind sponge, as there was no air circulation in the room. The data was recorded with a 4-channel B&K Photon+ data recorder. During the measurements, only the violinist was in the room (Figure 5), the person performing the measurements was in the adjacent observation room.

Figure 5. *The measurement setup in semi-anechoic chamber*

6. PRESENTATION AND ANALYSIS OF MEASUREMENT RESULTS

Time domain investigations

The duration of the measurements fell between 35 and 50 s, during which time we recorded 5 to 6 cycles (1 cycle = 1 pull and 1 tow phase of the bow) with the same bowing technique. These were repeated with all three investigated bowing techniques for all 4 violin strings. The time signals were processed with free audio editing software Audacity and GNU/Octave. Figure 6 shows the time signals related to the A-string as an example. It should be noted that the raw time signals were converted to *.wav format for further processing, so the real amplitude values (sound pressure) cannot be interpreted, they are lost. However, the relation of the individual amplitudes to each other remains.

The shapes of each cycle are visibly different, both in form and amplitude. The middle diagram of Figure 6 shows the sound of playing with the highest bow force. Its amplitude is expected to be the largest. We cannot determine much more than this from the shape of the time signals, so additional procedures and methods are needed. We will first examine some psychoacoustic metrics (Genuit, 2010) used to describe the nature and psychological effects of noise.

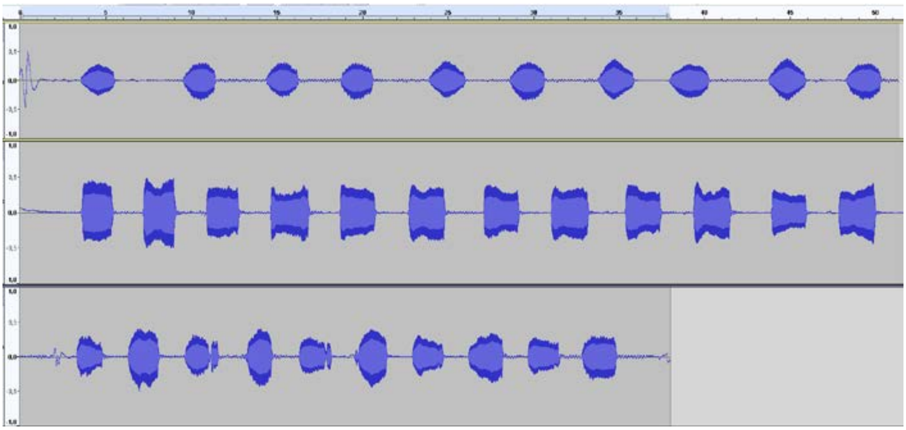


Figure 6. *The time signatures for the A string on the left channel (top: low force; middle: high force; bottom: transverse)*

The first is loudness, which is the subjective perception of sound pressure. The study of perceived loudness belongs to the field of psychoacoustics and uses the methods of psychophysics. According to Stevens' definition, 1 sone loudness corresponds to a loudness level of 40 phons (1 kHz sound at a sound pressure level of 40 dB) and is a quantity that characterizes the feeling of loudness.

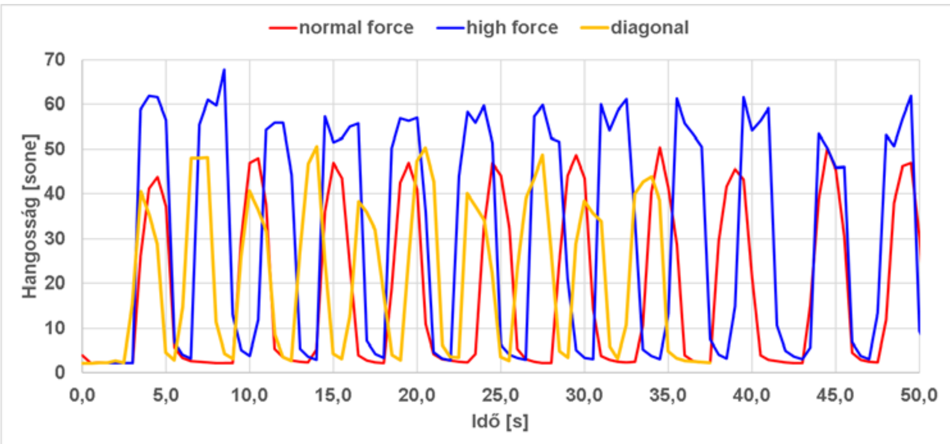


Figure 7. *Development of the loudness values (according to Zwicker) during the playing of the A string*

Figure 7 shows that the loudness of the A sound produced during the high force bow is indeed the highest, while in the other two cases their value is similar.

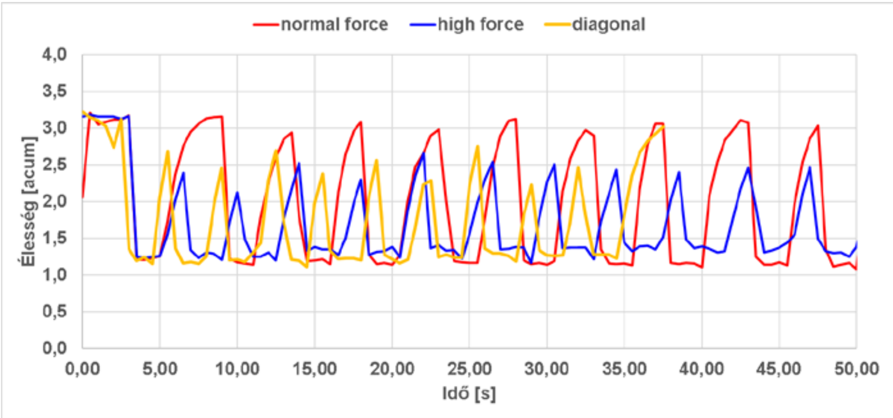


Figure 8. *Development of the sharpness values during the strumming of the A string*

Figure 8 shows that the acoustic sharpness during the three types of bows does not essentially differ from one another. In relation to the figure, it should be noted that, in contrast to the curves in Figure 7, the higher values are in the bow breaks, so the lower values must be taken into account.

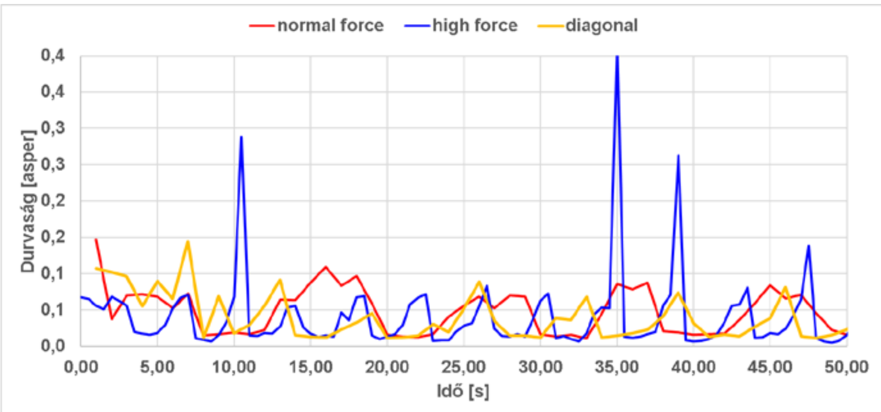


Figure 9. *Development of the sharpness values during the strumming of the A string*

Figure 9 shows that the acoustic roughness during the three types of sounding is essentially no different from each other, or their value is very low. Of course, this was to be expected due to the nature of the sound. In relation to the figure, it should be noted that, in contrast to the curves in Figure 7, the higher values are in the stroke breaks, so the lower values must be considered from the point of view of the analysis.
In summary, it can be said that the analysis of psychoacoustic measures is only limited or not at all suitable for clearly distinguishing the bowing techniques.

Frequency domain investigations

For further processing, we cut out the relevant time periods from the time signals according to Figure 6 and converted them individually to the frequency domain using the FFT transformation (Fast Fourier Transformation). The average spectra obtained in this way are shown in Figure 10 on the example of the A-string. The display range is 200 – 20000 Hz. The diagrams clearly show the fundamental tone of the A string at 441 Hz and the large number of harmonics, which, together with the fundamental tone, result in the unique sound of the bowed violin. Of course, not only the string played contributes to the timbre of the sound, but also the design of the instrument body, the materials used, and the method of production. Also, we must not forget about the design of the bow, the materials used for it, or nor about bowing technique.
At first glance in Figure 10, there is not much difference between the spectra. In the range from 200 to 20000 Hz, we see many peaks. In all three cases, the individual peaks have roughly the same amplitude up to about 7000 Hz, although in the case of high force bowing, the fundamental harmonic has the highest value of all three. Above 7000 Hz, the peaks of the middle spectrum (the high force bowing) are higher compared to the other two spectra.
Another feature that can be noticed in the spectra is that some non-integer harmonics appear in the middle and lower spectra, i.e. the 1.5th, 4.5th, 7.5th, 10.5th, 13.5th harmonics. Comparing the amplitudes of these non-integer harmonics, we can see that they are approximately 25% higher in the case of diagonal bowing. Our task is therefore to quantify these differences for a more accurate analysis.
Electroacoustic devices can be characterized by specifying the value of total harmonic distortion (THD): the ratio of harmonics appearing at the output of amplifier relative to the fundamental harmonic. For such devices, it is desirable that the amplitude of the harmonics be small compared to the amplitude of the fundamental harmonic, since the amplifier's task is to transmit the input signal without converting it. The relevant literature considers a THD value above 1% undesirable for amplifiers.

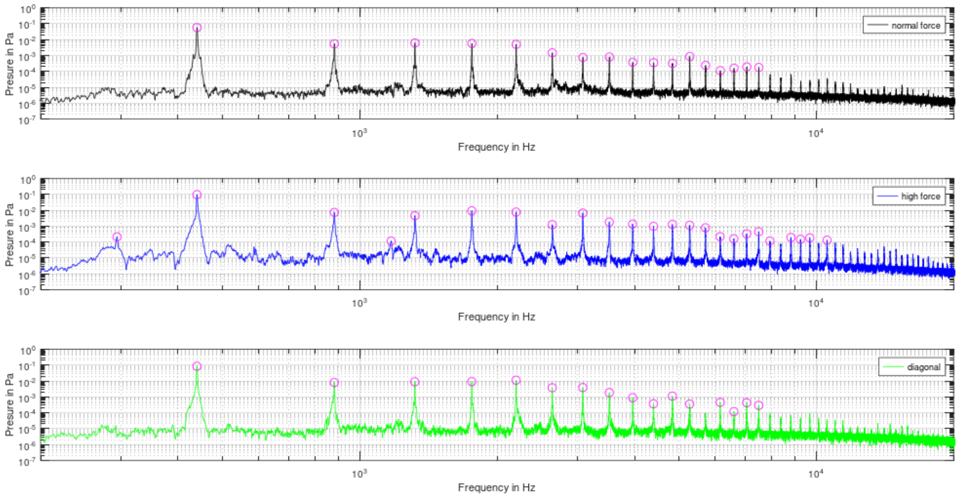


Figure 10. *Frequency spectra for the A string*
(top: low power; middle: high power; bottom: transverse)

In the case of a music instrument, of course, it is not desirable that only the fundamental harmonic emitted by the instrument should appear. Because of the presence of harmonics, we can distinguish between instrument sounds, so a kind of THD increase is necessary. THD can be used to quantify the difference between instrument tones using even number and odd number harmonics. THD can be calculated using the following equation:

$$THD = 100 \cdot \frac{\sqrt{p_2^2 + p_3^2 + \cdots p_n^2}}{p_1} \ [\%] \tag{2}$$

where p denotes the amplitude of the sound pressure measured by the microphone in Pa.

To perform the THD calculations, we used the previously mentioned spectra as a basis (Figure 8), and to perform the operations, we created a GNU/Octave program. It reads the spectra as ASCII files, finds the peaks of the spectra (indicated by purple ◊'s on the peaks in Figure 8) and calculates the THD based on the peak values found. After completing the calculations, we get the following percentage values of THD for the A string

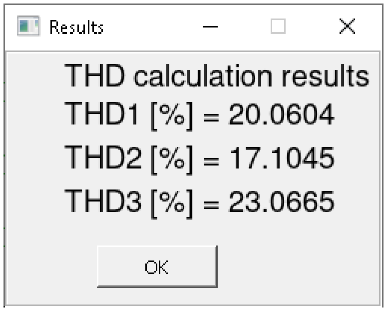
normal bow (THD1)	
high force bow (THD2)	
diagonal bow (THD3)	

Figure 11. *Results of the THD calculations*

It can be seen from the results that a clear difference can be established between the THD values of the bowing techniques. Taking the value of normal bowing as a reference value, bowing with high force means a decrease in THD value of about 15%, while diagonal bowing results in a 15% increase in THD. The former can be explained by the fact that the higher bowing force dampens some of the harmonics, and the latter by the appearance of additional harmonics. We have already described the latter in connection with odd number of harmonics.

Next, we examine the inharmonicity of the overtones. Musical inharmonicity shows the deviation of the components of a spectrum from the harmonic. Accordingly, the lines of the inharmonic spectrum are not equal, i.e. the frequencies of the overtones are not exactly integer multiples of the fundamental tone. The sound spectrum of ideal vibrating media (e.g. ideal vibrating string, ideal vibrating air column) serving as a model for some musical instruments is harmonic, but real instruments usually show inharmonicity (Murray, 2021). If the spectrum shows a small deviation from the harmonic (e.g. for piano, guitar and strings), then many listeners perceive it as close to harmonic, and inharmonicity affects the roughness of the sound. In other cases, the partial tones are scattered in the soundscape, not close to the frequencies corresponding to the harmonic, in which case, when a musical note is played, in some cases, the sensation of several separate sounds occurs at the same time (for example, percussion instruments with wooden or metal soundboards). In the extreme case, if the components are densely arranged in the inharmonic soundscape.

So, let us examine the magnitude of the inharmonicity for the case of the 3 types of string treatment. The results are shown in Table 1. The table's ref. column marked shows the theoretical base and harmonics of the 441 Hz sound A. The normal, high, and diagonal columns show the frequencies of the fundamental and harmonics of the tone A excited with three types of bowing.

Table 1

Comparison of inharmonicity in the case of different bowings techniques

	Ref	normal	Δf to ref	high	Δf to ref	diagonal	Δf to ref
Nr.	*Hz*	*Hz*	*Hz*	*Hz*	*Hz*	*Hz*	*Hz*
1.	**441**	**441**	*0*	**441**	*0*	**441**	*0*
2.	**882**	**881**	*-1*	**881**	*-1*	**881**	*-1*
3.	**1323**	**1322**	*-1*	**1322**	*-1*	**1321**	*-2*
4.	**1764**	**1762**	*-2*	**1761**	*-3*	**1761**	*-3*
5.	**2205**	**2203**	*-2*	**2201**	*-4*	**2202**	*-3*
6.	**2646**	**2643**	*-3*	**2642**	*-4*	**2642**	*-4*
7.	**3087**	**3083**	*-4*	**3081**	*-6*	**3082**	*-5*
8.	**3528**	**3524**	*-4*	**3522**	*-6*	**3522**	*-6*
9.	**3969**	**3965**	*-4*	**3962**	*-7*	**3962**	*-7*
10.	**4410**	**4405**	*-5*	**4402**	*-8*	**4400**	*-10*
11.	**4851**	**4846**	*-5*	**4842**	*-9*	**4842**	*-9*
12.	**5292**	**5286**	*-6*	**5282**	*-10*	**5282**	*-10*
13.	**5733**	**5726**	*-7*	**5722**	*-11*	**5722**	*-11*
14.	**6174**	**6166**	*-8*	**6159**	*-15*	**6163**	*-11*
15.	**6615**	**6607**	*-8*	**6601**	*-14*	**6603**	*-12*
16.	**7056**	**7047**	*-9*	**7041**	*-15*	**7043**	*-13*
17.	**7497**	**7488**	*-9*	**7482**	*-15*	**7482**	*-15*

The columns next to them show the deviations compared to the values in the reference column. An inharmonicity can be observed even in the case of the A note played with normal pulling force, which reaches 8-9 Hz in the case of higher frequency harmonics.

This difference is even higher than the other two sounding modes, reaching a value of 15 Hz. In these two latter cases, however, the differences are essentially the same. It can be concluded that the diagonal string treatment increases the inharmonicity, but compared to a strong string, this does not justify the unpleasant acoustic experience.

7. Summary and Conclusion

Our investigations showed that the finding of differences between the bowing techniques is a tough undertaking despite of the subjective clearly audible differences. Time and frequency domain methods were investigated and as a result we can state that the frequency domain method based on the THD is capable to describe the differences in form of quantitative and qualitative numerical values. The results are very similar for the other G, D, E strings too. Nevertheless, the extension of our investigations is planned to investigate other methods, such as autocorrelation, wavelet, Cepstrum, etc. to achieve more accurate distinguishing.

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