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The impact of materials type used to excite a cello strings on its sound

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Abstract The aim of this paper is the impact of popular textile materials used to excite cello strings on its sound and compare it with the sound obtained using a bow. The sound-generating mechanism was designed and manufactured to allow for the regulation of the tension of the selected material, similarly to the tension of the horsehair in a cello bow. The mechanism allows for the generation of sound in a continuous manner, ensuring repeatability. The influence of individual materials used to excite cello strings was determined based on acoustic measurements using a multi-channel recording system. The paper presents the spectra of the cello sound and determines the spectral centroid, which is a decisive parameter related to the timbre of the instrument.

Keywords: cello sound generation mechanism, cello sound, spectrum, acoustic measurements.

1. Introduction

The sound of a cello is influenced by many factors, including the type of material and the age of the body [1], the arrangement and geometry of the soundpost and bass bar, the type of strings used, the geometry and arrangement of the bridge, the type and movement of bow used [2] and even the material of the cello's endpin [3]. The purpose of constructing the described mechanism and testing the textile materials is to ensure repeatable excitation of the strings in order to determine the effect of modifying individual elements of the structure of stringed instruments on its sound. One of the most important elements of the cello structure is the bridge, whose role is to transfer the vibrations of the strings to the sound box. Some works are related to the analysis of the influence of bridge geometry on its resonance frequencies using the FEM [4]. The influence of changing the geometry and construction parameters of the bridge on the sound of the cello was also analysed [5]. The type of cello strings used also affects the timbre of the instrument. Nowadays, due to their greater durability and tuning stability, cello strings are made of metal [6]. Strings made of lower quality materials are more susceptible to defects such as "wolf tones", that is undesirable tones in the sound spectrum [7]. This results in sounds with a characteristic timbre that is unpleasant and resembles trembling. The soundpost consists of a thin piece of wood in the shape of a cylinder placed inside the sound box, directly under the top plate of the box and near the bridge, in a line perpendicular to the top plate of the sound box. The soundpost plays the role of transmitting vibrations between the top and bottom of the sound box. The sound of the cello can be produced in a variety of ways, but is most often produced using a bow. The bow consists of an elastic stick with horsehair attached to the ends. At one end is a frog, which, by sliding along the stick, tightens the hair. When the bow is not in use, the hair should hang loosely between the ends of the stick to maintain its elasticity. The sound of the generated sound of the cello depends, among other things, on the articulation, i.e. the way the sound is generated by the musician. The sound is influenced by both the pressure force and the speed of feed and the place where the bow is applied to the string [8, 9]. In the case of vibroacoustic studies aimed at determining the influence of individual elements of the cello's construction on its sound, it is extremely important to ensure the repeatability of the generated sound. The sound generated by a musician is not repeatable, which is reflected in both the amplitude and the spectrum of the signal. The literature contains various methods and mechanisms of generating sound in stringed instruments [10, 11]. This paper describes the cello's sound-generating mechanism and a description of popular textile materials used instead of a bow to generate sound. The mechanism described in the paper can be used in vibroacoustic studies of the influence of individual elements of the construction of stringed instruments. The presented results can be helpful in selecting the appropriate material for generating sound in similar sound generation mechanisms in various stringed instruments.

Section 2 describes the theoretical foundations and parameters used to determine the influence of individual materials on the sound of the cello. Section 3 describes the construction of the cello sound generating mechanism and the speed and direction of rotation control system. Section 4 describes the research methodology, basic assumptions and measurement equipment. Section 5 describes the type of materials used in the studies to excite the sound of the cello. Section 6 contains the measurement results.

2. Theoretical foundations

The methods of analyzing the similarity of sound signals were mainly taken from speech recognition methods. The parameters of signals can be considered in both the time and frequency domain. In the time domain, we can distinguish the signal envelope, which illustrates the changes in the signal volume in the individual phases of the signal duration (attack, decay, sustain and release phase) [12, 13]. Other measures used in the time domain are related to energy level and zero crossing rates parameters of the signal [14, 15]. Time-domain parameters may not be sufficient in terms of signal comparison efficiency; then frequency-domain parameters turn out to be better. In this paper, the analysis of measurement results focuses mainly on the comparison of sound spectra and frequency-domain parameters. The timbre of a sound depends mainly on the amplitude of the fundamental tone and the harmonic components of the signal. Spectral parameters are determined based on the analysis of the Fourier spectrum of the signal.

Parameters that are often used in the frequency domain are the m-th order spectral moments (m = 0,1,2...). Spectral moments are an analogue for the statistical description of the data distribution. The main parameter determining the sound timbre is the first-order spectral moment, the interpretation of which is the spectral centroid [15, 16]

$$\mu_1 = \frac{\sum_{k=1}^{K} f(k) X(f_k)}{\sum_{k=1}^{K} X(f_k)}, \tag{1}$$

where μ_1 – spectral centroid [Hz], $f(k)$ – frequency of the k-th frequency bin [Hz], $X(f_k)$ – amplitude of the k-th frequency bin [-].

The second-order normalized central moment is referred to as spectral spread or spectral standard deviation and denotes the spread of the spectrum around its mean value

$$\mu_2 = \sqrt{\frac{\sum_{k=1}^{K} (f(k) - \mu_1)^2 X(f_k)}{\sum_{k=1}^{K} X(f_k)}}. \tag{2}$$

The third-order normalized central moment is the spectral asymmetry, or skewness, which gives a measure of the asymmetry of the spectrum around its mean value

$$\mu_3 = \frac{\sum_{k=1}^{K} (f(k) - \mu_1)^3 X(f_k)}{\mu_2^3 \cdot \sum_{k=1}^{K} X(f_k)}. \tag{3}$$

Spectral kurtosis is a parameter that is a measure of spectral flatness and provides a measure of the flatness of the spectrum around its mean value

$$\mu_4 = \frac{\sum_{k=1}^{K} (f(k) - \mu_1)^4 X(f_k)}{\mu_2^4 \cdot \sum_{k=1}^{K} X(f_k)}. \tag{4}$$

Tristimulus is a parameter describing the ratio of the energy of the first harmonics to the all harmonics present in the sound spectrum [12, 14]. The T_1 value describes the contribution of the first harmonic to all harmonics of the spectrum

$$T_1 = \frac{X(f_1)}{\sum_{h=1}^{H} X(f_h)}, \tag{5}$$

where $X(f_1)$ – amplitude of the first harmonic, $X(f_h)$ – amplitude of the h-th harmonic, H – number of harmonics.

The T_2 value describes the ratio of the sum of the amplitude of the second, third and fourth harmonic energy to the sum of the amplitudes of all harmonics

$$T_2 = \frac{X(f_2) + X(f_3) + X(f_4)}{\sum_{h=1}^{H} X(f_h)}, \tag{6}$$

where $X(f_2)$, $X(f_3)$, $X(f_4)$ – amplitude of the second, third and fourth harmonic respectively, $X(f_h)$ – as above. A higher value of this parameter means a greater concentration of energy in the first harmonics in relation to the energy in the entire signal.

The T_3 value describes the share of the fifth and higher harmonics in the sound spectrum

$$T_3 = \frac{\sum_{h=5}^{H} X(f_h)}{\sum_{h=1}^{H} X(f_h)}, \quad (7)$$

where $X(f_h)$ – amplitude of the h-th harmonic, H – number of harmonics. The higher the value of this parameter, the greater the share of these higher harmonics in the entire spectrum, and therefore the sound can be perceived as brighter.

The values of the parameter related to the content of the energy of the harmonic components were also compared, describing the ratio of the noise energy E_N to the total energy of the signal E_T, called noisiness S (8). The value of the noise energy can be approximately determined by subtracting the energy of the harmonic components E_H from the total energy of the spectrum [15]. A higher value of the noisiness S means that a larger part of the signal energy comes from non-harmonic components, which makes the timbre may be perceived as unpleasant

$$S = \frac{E_N}{E_T}, \quad (8)$$

where $E_T = \sum_{k=1}^{K} X(f)$ – total energy of the spectrum, $E_N = E_T - E_H$ – noise energy, $E_H = \sum_{k=1}^{K} X(f_k)$ – energy from the harmonic components.

3. Construction of a sound generating mechanism

There are numerous examples of devices used to generate sound in the literature. Some use simpler mechanisms to move a bow or other element that rubs the strings [10], while other more advanced robots imitate the arm of a musician [17, 11]. The design of the cello sound generation mechanism was inspired by the mechanism made by Hathaani [8]. Compared to the previous version [3], the DC motor was replaced with a stepper motor. Stepper motors allow for greater torque without the need for a gear, which results in quieter operation of the mechanism. The mechanism construction allows the string friction belt to be replaced and its tension to be adjusted using a nut (No. 13 in Fig. 1) thanks to the use of a tension roller (No. 2 in Fig. 1). The body and most of the elements of the device were made using 3D printing technology.

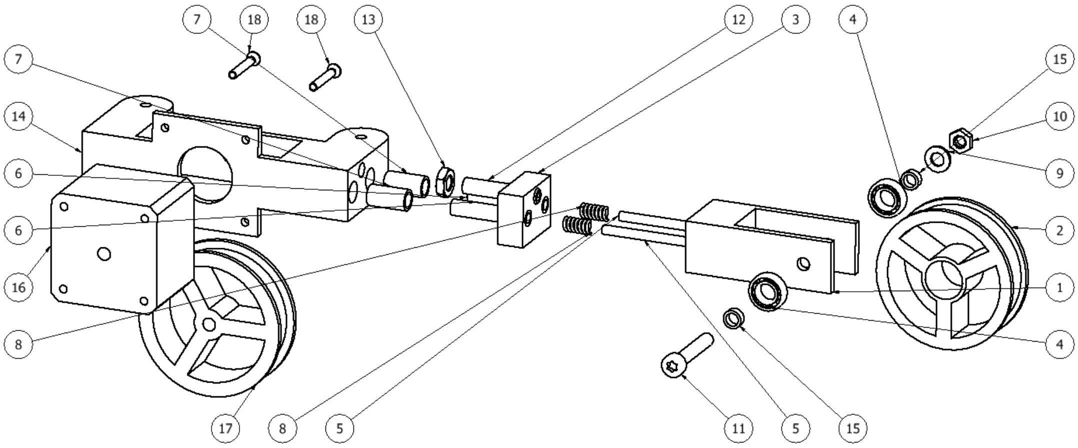

Figure 1. Schematic of the sound generating mechanism: 1 - fork, 2 - tension roller, 3 - belt tension adjuster, 4 - ball bearing, 5 - rod, 6 - stabilizing sleeve I, 7 - stabilizing sleeve II, 8 - spring, 9 - washer, 10 - M5 nut, 11 - M5 screw, 12 - M6 threaded pin, 13 - M6 nut, 14 - body, 15 - stabilizing sleeve III, 16 - stepper motor, 17 - drive wheel, 18 - M3 screw.

The control system consists of passive electronic components and does not require microcontroller programming [18]. The main element is the popular A4988 stepper motor driver set to microstepping mode with a resolution of 1/16. The appropriate selection of capacitors C1 and C4 allows for rough speed adjustment, while fine adjustment is performed using potentiometer R3 (Fig. 2). For the device configuration used during the tests, the maximum and minimum belt feed speed limits were:

v_{max} = 0.662 m/s and v_{min} = 0.007 m/s. The belt feed speed was set using a potentiometer, which was v = 0.276 m/s during the tests and was the same for all variants. The electronic control system allows you to adjust the speed of the stepper motor as well as change the direction of rotation. The stepper motor supply voltage was set at 12 V and the logic part of the system is supplied with 5 V.

a) b)

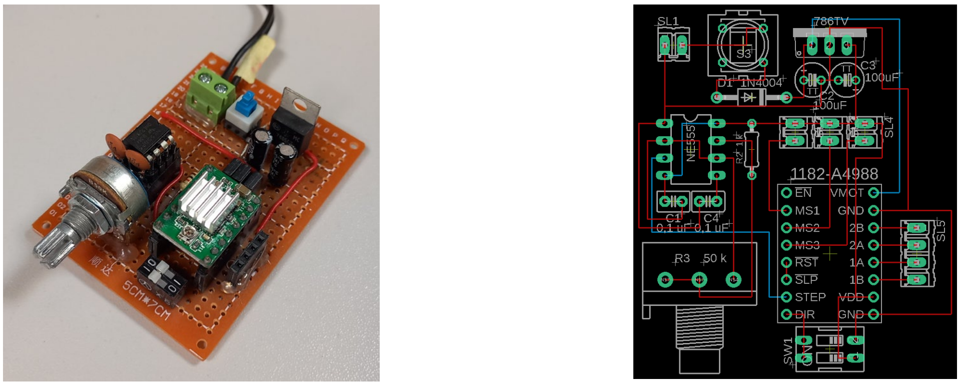

Figure 2. Stepper motor control system: a) assembled device, b) arrangement of components on the PCB.

The mechanism was attached to an aluminum profile, which in turn was attached to a wooden frame holding the cello (Fig. 3). The wooden structure holding the cello had to be adapted to allow the belt angle to be changed to a large range to enable sound generation on all the instrument strings.

a) b)

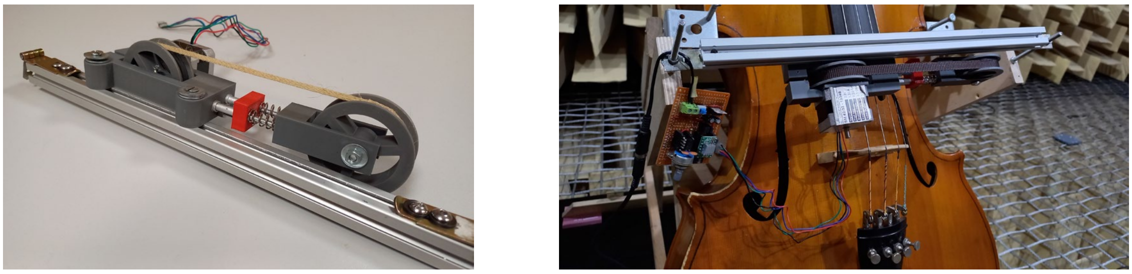

Figure 3. The constructed device for generating cello sound: a) attached to an aluminum profile, b) attached to a wooden frame during measurements of the sound generated on the string.

4. Research methodology and basic assumptions

The wooden frame structure in which the cello was mounted had to be adapted to enable excitation on each of the four strings of the instrument. Long threaded pins were mounted to hold the aluminum profile on which the device was mounted. Hinges were attached to the ends of the profile, allowing the material to be positioned at the right angle to the excited selected string. The pressure force of the belt on the string could vary depending on the belt material and the selected string, however, during measurements for a given variant on a given string, a repeatable pressure force was ensured by the same positioning of the device relative to the string. The wooden structure holding the cello was placed on a plywood board in an anechoic chamber. Sylomer pads were placed at the junction of the wooden frame with the plywood board and the plywood board with the floor structure elements in the anechoic chamber. In acoustic tests used to determine the effect of modifying individual elements of an instrument's construction on its sound, the most important thing is the repeatability of excitation the instrument's strings to vibrate.

The measurements were taken for the open strings A, D, G, C, whose frequencies were: 220 Hz, 147 Hz, 98 Hz, 65 Hz, respectively [19]. During the measurements, the strings that were not taken into account in the measurements were damped with felt to eliminate additional frequency components in the sound spectrum. The measurement was performed using five microphones G.R.A.S 46AE (Fig. 4 a), taking into account the instrument's directivity characteristics. The final spectrum represents the average value of all microphones. The microphones were arranged evenly in a circle with a radius of 1 m, at a height of 1.1 m, which corresponded roughly to the height of the ear of a seated recipient (listener). The microphones were connected to B&K 16-channel conditioning amplifier types 2694 from which the signal was routed to the

Focusrite 18i20 audio interface. Measurements were carried out in the Matlab environment, recording five signal paths of 30 s duration. The signal from the calibrator (B&K, type 4231) was also recorded and used to calibrate the microphones. In analysis, the final spectrum represents the average value from all microphones and the number of repetitions, determined with a resolution of 1 Hz. In the calculations it was assumed that the spectral domain is represented by the amplitudes and frequencies of the harmonic components. Values were calculated based on the peak amplitudes corresponding to the individual harmonics of the spectrum. Due to the frequencies of individual harmonics, the range of analysed spectral frequencies was limited to 20 Hz to 4000 Hz. Calculations were performed in the same manner for all measurement variants.

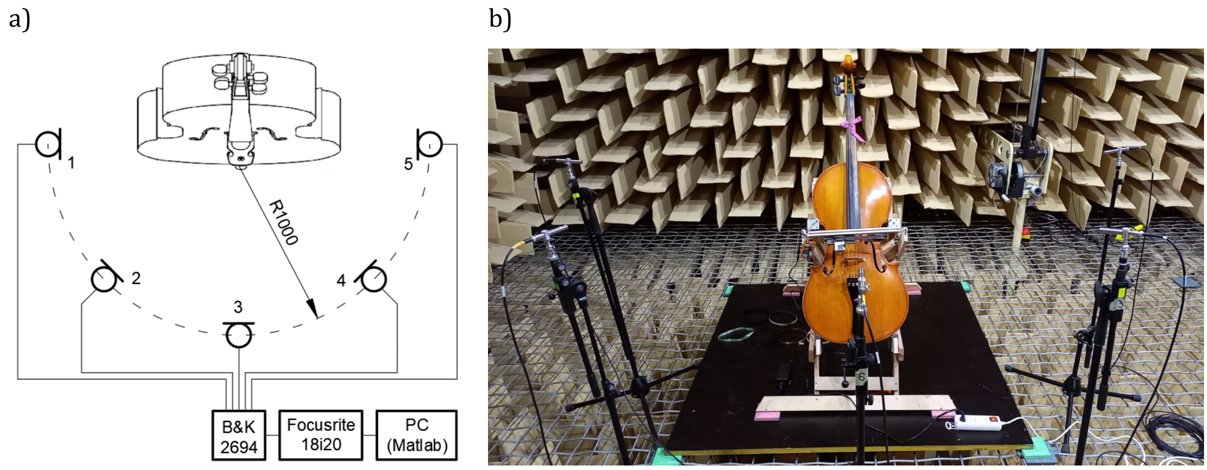

Figure 4. Measurement setup: a) scheme, b) assembled measuring setup in an anechoic chamber

5. Types of materials used to excite cello strings

The research carried out was aimed at comparing textile materials used to excite cello strings and selecting those that will generate a timbre most similar to the timbre of playing with a bow. Of course, the best solution would be to use horsehair, but despite numerous attempts to make a loop, due to both the difficulty of connecting the ends and the breaking of individual hairs, these attempts ended in failure. Numerous attempts were also made to create a loop using rope made of various materials, but due to the significant forces caused by the tension of the tension roller and friction on the strings, the loop broke. It was decided to use textile materials in the form of 10 mm wide and 475 mm long tape so that they could be easily inserted into the device's rollers. Eight readily available materials were selected, the ends of which were glued together with cyanoacrylate glue to form a loop. To increase friction, the surface of the materials was smeared with a solution of fine pieces of rosin used to lubricate the bow and alcohol. Immediately before the measurements, each material was additionally lubricated with rosin. The application of rosin was evenly applied across the entire width along the strip, both in the case of liquid rosin and in the traditional way of using standard rosin (just like the bow before starting to play). The final materials selected for testing along with the symbols used in further analysis are shown in Fig. 5.

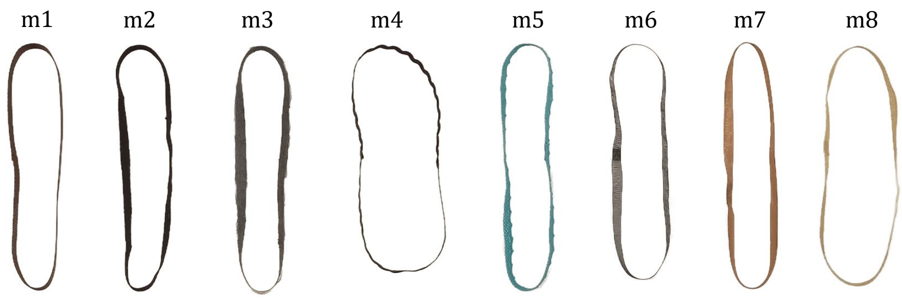

Figure 5. Types of materials used to excite cello strings: m1 - nylon tape, m2 - cotton, m3 - cotton with the addition of polyester, m4 - polyester wavy ribbon, m5 - cotton lace tape, m6 - organza, m7 – synthetic satin, m8 – linen.

6. Results

The presented research results compare the sound generated using all eight variants of the selected materials with the sound generated using a bow and the previous version of the mechanism. In total, measurements were performed for ten variants of excite the cello strings in different ways. The individual measurement variants are described as: bow – excitation of the strings with a bow, w – excitation of the strings using a rotating wheel of another mechanism [3], m1 – nylon tape, m2 – cotton, m3 – cotton with the addition of polyester, m4 – polyester wavy ribbon, m5 – cotton lace tape, m6 – organza, m7 – synthetic satin, m8 – linen. Additionally, in order to compare the noise generated by two mechanisms for generating the sound of the cello, measurements of the sound pressure level *Lp* were taken during the operation of the devices without load (i.e. without generating sound). For the other mechanism, two measurements were made using five microphones and the results were averaged. For the new mechanism, three measurements were made (for three different materials) using five microphones and the results were also averaged. The values obtained in individual measurements of a given mechanism did not differ significantly from each other. The following results were obtained: another/ previous mechanism – 58.1 dB, the new mechanism – 48.8 dB. Higher values of the acoustic background noise generated by the another mechanism are caused by the use of a gear transmission to the DC motor in order to increase the torque. The new device uses a stepper motor and does not require a gear transmission.

The figures below (Fig. 6) show the sound spectrum along with the marked spectral centroid frequency for string excited with a bow. This is the reference spectrum to which the remaining measurement variants refer.

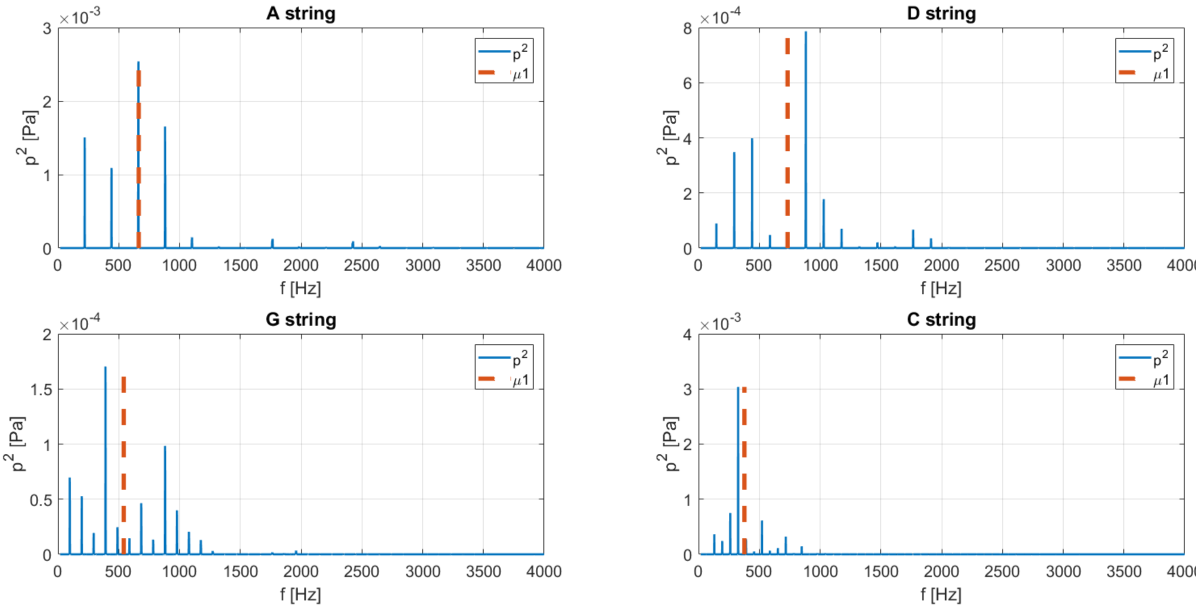

Figure 6. Sound spectrum for excited strings with a bow – reference spectrum.

The figures in Fig. 7 show a comparison of the spectral centroid values for all measurement variants, with distinction made between individual strings.

Based on the analysis of the spectral centroid frequencies, it can be seen that almost all (except for the A string) of the analyzed methods of exciting the cello strings generate a darker timbre of sound than excitation with a bow. It is difficult to clearly determine the variant corresponding to the darkest and the brightest tone of the instrument. For strings A, D, G, C, the lowest values of the spectral centroid are achieved by variants: w, m1, m2, m4 and the highest values: m7, w, m6 and m3 respectively.

It is also difficult to clearly indicate the material whose sound is most similar to the sound obtained with a bow. For all measurement variants, spectral moments were calculated. Materials for which the values of spectral moments are closest to the spectral moments of the reference spectrum are presented in Table 1.

Table 1. Variants whose spectral moments were closest to the spectral moments of the reference spectrum for individual strings.

Spectral moments															
A string				D string				G string				C string			
$\mu1$	$\mu2$	$\mu3$	$\mu4$	$\mu1$	$\mu2$	$\mu3$	$\mu4$	$\mu1$	$\mu2$	$\mu3$	$\mu4$	$\mu1$	$\mu2$	$\mu3$	$\mu4$
m6	m3	m3	m7	w	m7	w	m7	m6	m7	m7	m1	m7	w	m6	m5

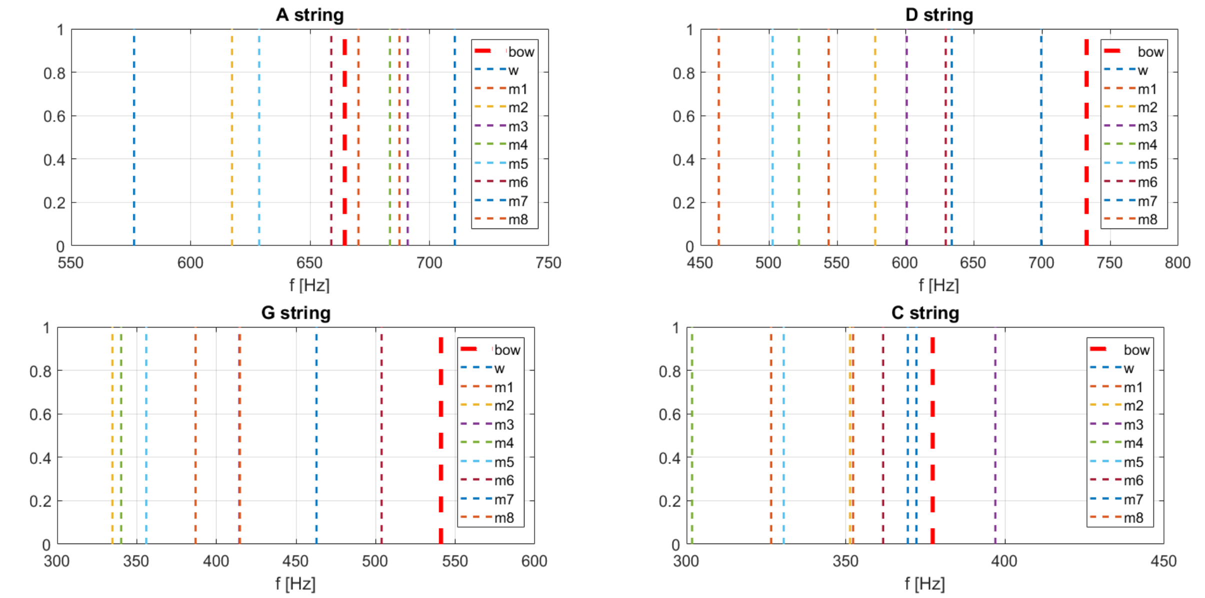

Figure 7. Spectral centroid of the analyzed variants used to excite cello strings.

Analyzing the remaining spectral moments, i.e. spectral spread and kurtosis, the variant that shows the greatest similarity to the sound obtained with a bow is the m7 variant, which corresponds to the material - synthetic satin tape. Taking into account the previously mentioned spectral moments as well as the spectral skewness, the materials used in variants m6 and m7 can be considered as those that show the greatest similarity to the sound obtained with a bow.

The figures below present the values of the tristimulus T_1, T_2, T_3 parameters for all measurement variants, differentiated by individual strings.

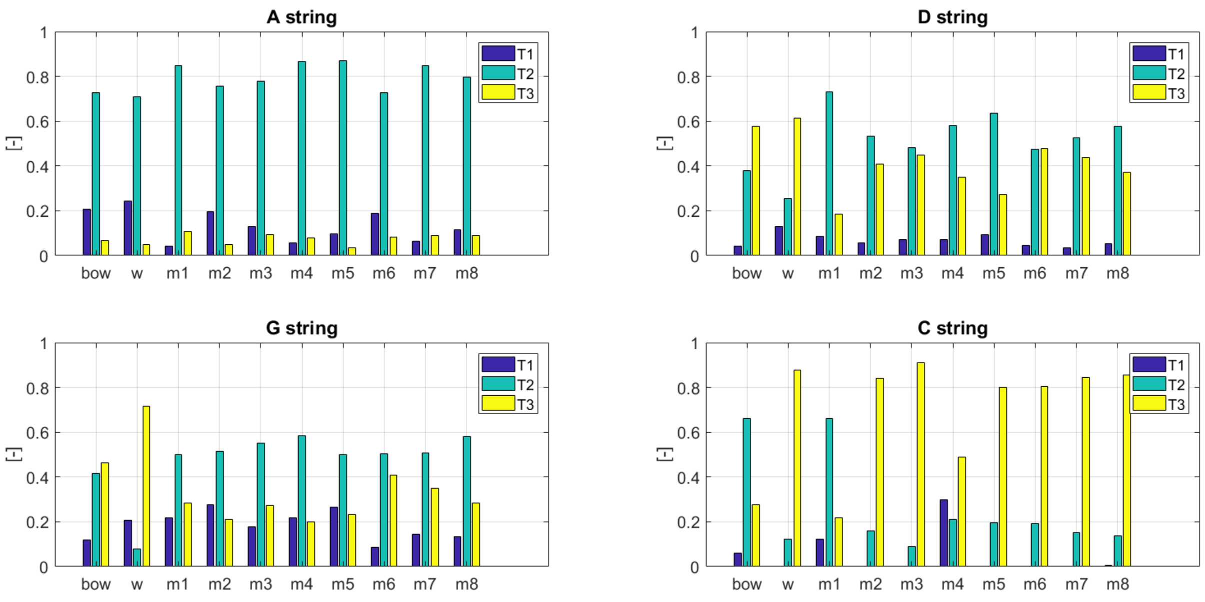

Figure 8. Tristimulus values of individual measurement variants for each string.

The variants for which the T_1, T_2 and T_3 values are closest to the values obtained from the reference spectrum are presented in Table 2.

Table 2. Variants whose tristimulus values were closest to the tristimulus values of the reference spectrum for individual strings.

A string			D string			G string			C string		
T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3
m2	m6	m4	m6	m6	w	m8	m1	m6	m8	m1	m1

The values of the noisiness S of the individual measurement variants for each string are given in Table 3 (the lowest values are marked in bold).

Table 3. Noisiness S values of the individual measurement variants.

	w	m1	m2	m3	m4	m5	m6	m7	m8
S (A string)	0.27	0.17	0.54	0.09	0.23	0.60	**0.08**	0.16	0.18
S (D string)	0.54	0.31	0.29	0.31	0.38	0.56	**0.12**	0.52	0.34
S (G string)	0.74	0.42	**0.31**	0.45	0.41	0.59	0.52	0.43	0.43
S (C string)	0.21	0.84	0.20	0.52	0.52	0.43	**0.09**	0.26	0.35

7. Conclusion

The paper analyses the influence of readily available textile materials that can be used to excite the cello strings on the cello's timbre and comparison with the timbre generated by a bow. In order to carry out the research, a cello sound generating mechanism was designed and manufactured, which can also be used for other bowed string instruments. The mechanism enables the generation of repeatable sound in a continuous manner, so it can be helpful in performing vibroacoustic studies, including the influence of individual elements of the cello structure or their modification on its sound. The paper presents details of the mechanism construction and the results of research related to various types of materials used to generate sound. The main advantages of the mechanism include a lower level of acoustic background compared to other analysed devices, the possibility of using different materials and changing the speed and direction of rotation.

The sound spectrum depends on many parameters not only related to the frequency of a given string, but also to the way the sound is produced. The individual variants of the cello sound generation methods were compared with each other based on parameters determined from the signal in the frequency domain. Based on the analysis of the spectral parameters, it is difficult to clearly indicate a material that would have a decisive influence on the cello's timbre. It is also difficult to clearly indicate a material whose sound timbre will be most similar to the sound timbre obtained with a bow. Different materials achieved minimum and maximum values of the spectral centroid for different strings. Taking into account the sum of the distances of the spectral centroid frequencies from all strings for individual variants and their minimum or maximum value, it is easier to state that the material with the darkest sound is variant m5 - cotton lace tape, while the brightest sound can be obtained using variant m7 - synthetic satin. Analyzing by analogy the variant whose sound shows the greatest similarity to the sound obtained with a bow is m6 - organza. This is also confirmed by the analysis of the frequency value of the spectral centroid, which is mainly a parameter that determines the sound timbre. The most different sound timbre from that obtained with a bow can be obtained by using material from the m4 variant – polyester wavy ribbon. It can be also seen that the sound timbre generated by the bow is quite bright, as almost all variants for all strings (except the A string) generate a darker cello sound timbre. In the analysis of the tristimulus parameters, variant m6 appears for almost every string except for the C string. The noisiness value S reaches the lowest values for variant m6 for all strings except for the G string.

Taking into account all the values of the analyzed spectral parameters and the noisiness, it can be stated that the material whose sound is most similar to the sound generated by a bow is variant 6 - organza. The material that generates the darkest timbre of the cello sound using the mechanism is variant m5 - cotton lace ribbon, while the brightness tone can be obtained by variant m7 - synthetic satin.

When taking measurements, special attention should be paid to the stabilization of the instrument in a wooden frame. The best results can be obtained by taking measurements, if possible, with the cello mounted in the frame once.

Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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