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The cello sound generation mechanism in vibroacoustic studies of the impact of the endpin material on the cello sound

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Abstract The aim of the paper is to present the structure of the mechanism that excites the cello strings to vibrate, used in vibroacoustic research of the impact of the endpin material on the cello sound. The construction of the device is inspired by the hurdy-gurdy mechanism. In the acoustic study of string instruments, it is hard to take into account the human factor during the generation of sound. When playing an instrument, there is difficulty in obtaining repeatability of the generated sound, especially with a large number of repetitions. The presented device is particularly useful during vibroacoustic tests of bowed string instruments. It enables the generation of continuous sound and ensures the repeatability of excitation. In addition to the description of the construction of the mechanism, vibroacoustic tests related to the determination of the influence of the cello endpin material on its timbre were also presented. The impact of the endpin material on the cello sound was determined based on measurements as well as subjective impressions of the musicians.

Keywords: cello sound generating mechanism, vibroacoustic research, cello, cello endpin, spectrum, timbre.

1. Introduction

The cello is an acoustic bowed string musical instrument. Over the years, the shape and individual elements of the construction of this instrument have been modified. The modern cello is an interesting instrument, thanks to the innovations and improvements made to it. Some of these changes affected the timbre of the sound to a greater or lesser extent, including the number of strings, the presence of frets on the neck, the geometric dimensions of the body, the dimensions of the soundpost and the bass bar [1]. The length of the fingerboard and the angle of the neck relative to the body were also changed. The geometry of the bridge, the type of material from which the strings are made and the material of the endpin have also been modified. In acoustic instruments, many factors affect the sound, in addition to those mentioned above - the material and its age of the instrument body [2]. For string instruments, an important aspect is also the method of extracting the sound (articulation), i.e. the bow pressure force, the speed of movement and the place of applying the bow on the string [3]. To determine the elements that have the greatest impact on the sound of the instrument and the possibility of modifying these elements to improve the timbre of the instrument, research should be performed. Most often, these are acoustic and vibration tests as well as subjective tests. In the case of vibroacoustic tests, it is important to maintain the same conditions related to sound generation in order to determine the impact of modifications of individual elements of the instrument's construction on the sound. Various methods and mechanisms for generating sound in string instruments have been described in previous publications [4]. Some methods of generating sound use an additional element (other than the bow) to make the strings vibrate [3]. In the case of mechanisms using a bow, it is also possible to compare the effect of different types of bows on the sound of the instrument [4-7]. When a musician plays, it is difficult to maintain the repeatability of the generated sound and often, a large number of repetitions are required to average the result, which in turn extends the measurement time. The mechanism described in this paper is a device that enables vibroacoustic measurements to be performed while maintaining the repeatability of excitation. The sound can be generated continuously, which makes it possible to obtain an arbitrarily long time course recording for analysis.

Some musicians say that the material of the cello endpin affects the timbre of the cello. Initially, there was no endpin in the cello and the instrument rested on the ground, arm or leg of the musician. Later, due to the size of the instrument, everyday use items (such as a barrel or a stool) were also used to support the instrument [8]. In the 17th century, the endpin began to be used as an integral part of the instrument (they were originally made of wood). Then there were endpins with adjustable lengths. Nowadays, the endpin is a construction element that can be easily replaced without interfering with the construction of the instrument itself [9]. The paper also presents preliminary vibroacoustic and subjective studies related to the influence of the cello endpin material on timbre.

Section 2 describes the construction of the cello and the influence of the individual parts of the construction on the generated sound. Section 3 presents the mechanism for generating the cello sound along with its detailed structure. Section 4 contains a description of the measurement setup and a description of the cello endpins made of various materials used in the tests. Section 5 contains the type of performed analyses. Section 6 - obtained results.

2. Construction of the cello

The cello consists of several dozen individual parts, each of which has its specific function and some affect the sound of the instrument. Like other string instruments, the cello produces sound waves by vibrating the strings over a wooden body. The vibrations of the strings are transmitted through the bridge to the front plate of the body (Fig. 1) and then through the soundpost located inside the instrument to the back plate. The resonance body of the cello is the main element designed to amplify the sound of vibrating strings. The front plate is most often made of spruce and the back plate is made of maple, although other types of wood are also used. Nowadays, we can meet individual parts of the cello and even entire instruments made of carbon fiber.

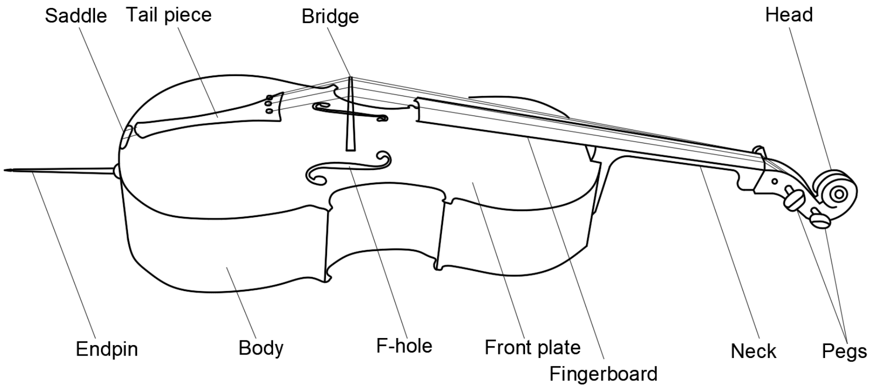


Figure 1. Scheme of the construction of a cello.

The frequency of a string's oscillations depends on its mass, linear density, and string tension (strength). The string vibrates at the fundamental frequency and the harmonic frequencies f_n of that frequency according to:

$$f_n = \frac{nv}{2l} = \frac{n}{2l}\sqrt{\frac{T}{\mu}} \tag{1}$$

where T – tension of the string [N], v – speed of sound [m/s], l – length of the string [m], $\mu = m/l$ – linear density [kg/m], m – mass of the string [kg].

Harmonics create a standing wave on the string between the string's fulcrums. The distance between the fulcrums, i.e. the length of the string, therefore affects the pitch of the fundamental tone. Shortening the string not only stiffens it but also reduces its mass without changing the ratio mass per unit length. The string is shortened by pressing it against the fingerboard by fingers.

The endpin of the cello is most often a rod made of metal, used to support the instrument on the floor, the length of which is adjusted by a screw. In most cases, during the transport of the instrument, the cello's endpin is hidden inside the body. The end of the cello's endpin has a pointed tip, so to prevent the leg from slipping on hard and smooth surfaces (e.g. in churches) or from damaging wooden floors, wooden pads are used. Cellos come in different sizes depending on the age of the players. The smallest cello size is 1/8 and the largest 4/4. A full-size cello (4/4) weighs approximately 3.5 kg.

3. Construction of a sound generating mechanism

The mechanism that causes the strings to vibrate is inspired by the hurdy-gurdy, where sound is produced by a string rubbing wheel that is built into the instrument body. In the hurdy-gurdy, the wheel is set in motion manually by means of a crank handle. The excitation mechanism to vibrate a cello string (frame and wheel) was designed and printed in a 3D printer. This mechanism consists of a frame attached to an aluminium profile and a DC motor with a toothed gear. In order to increase friction and improve the sound of the instrument, the surface of the wheel was smeared with liquid rosin. Liquid rosin was obtained by dissolving pieces of rosin used to lubricate the horsehair of the bow in alcohol. The aluminium profile was attached to the wooden frame on which the cello was placed. The pressing force of the wheel to the strings can be adjusted with the screw nuts (Fig. 2, item 9) on the threaded pin (Fig. 2, item 8). The change of the string was carried out by moving the body (Fig. 2, item 1) in relation to the aluminium profile by adjusting the screws (Fig. 2, item 5).

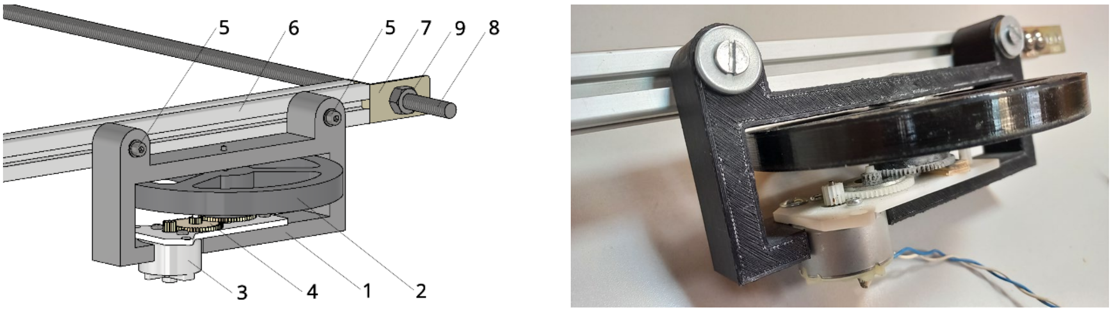


Figure 2. Construction of a sound generating mechanism (1 – body of mechanism, 2 – wheel, 3 – DC motor, 4 – gear, 5 – screws, 6 – aluminum profile, 7 – angle bar, 8 – threaded pin, 9 – screw nut).

3.1. Construction details of the mechanism

The body and the mechanism wheel were printed in 3D technology using the popular PLA material. The wheel (Fig. 2, item 2) has a diameter of 0,1 m. The diameter of the wheel has been chosen so that it is possible to excite only one string to vibrations with the right pressure. A 5V DC motor was used which the torque on the motor shaft 0.002 [Nm]. The torque was determined by measurements applying a variable mass at a known distance from the shaft axis. This distance was equal to the radius of the wheel mounted in the device frame. The maximum torque was determined for the largest mass for which the engine could work properly. The transmission of power from the motor shaft to the wheel rubbing the strings takes place via a toothed gear. A two-stage gear transmission was used, consisting of four gears with a number of teeth: $z1 = 12, z2 = 56, z3 = 12, z4 = 64$ (Fig. 3).

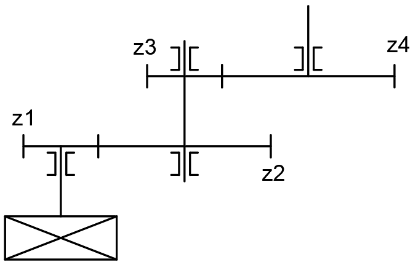


Figure 3. Gear scheme.

The total gear ratio of the two-stage toothed gear was calculated according to the formula [10]:

$$i_c = i_I \cdot i_{II} \tag{2}$$

where $i_I = \frac{z_2}{z_1}$ – gear ratio of the first stage of the gearbox, $i_{II} = \frac{z_4}{z_3}$ – second-stage gear ratio.

For the gear used, the total ratio is $i_c = 24.88$. Therefore, this gear causes an increase in torque (up to 0.05 [Nm]) and a decrease in the rotational speed (i_c – times) of the wheel rubbing the strings at the output of the gear ($i_c > 1$ – reducer).

4. Vibroacoustic measurements of a cello endpin

During the tests, it was important to keep the same measurement conditions. For the measurements, a wooden frame was designed and constructed (Fig. 4), which held the instrument immobile. The frame structure was hinged to the wooden plate constituting the ground. The frame consists, among others, of clamps that hold the instrument pointwise through vibration-isolating pads in order to eliminate the movement of the measuring setup during the replacement of the endpin. The instrument and the entire structure were placed on board made of plywood. In order to minimize the transmission of vibrations between the cello and the wooden frame as well as between the wooden frame and the plate on which the frame was placed, vibration isolation pads were used. The plywood board was also vibro-insulated from the floor in the anechoic chamber. The influence of vibrations of the wooden frame was not taken into account but ensuring the same excitation of the strings, possible vibrations of the wooden frame have the same effect for each type of cello endpins. The measurements were carried out in free field conditions - in an anechoic chamber. Three vibration sensors and a measuring microphone were used. One of the sensors was placed on the floor (0.01 m next to the endpin), and the other sensor was attached to the cello's body next to the hole for the endpin. The third vibration sensor was located between the resonance holes (f-hole) near the bridge. All sensors were fixed by wax.

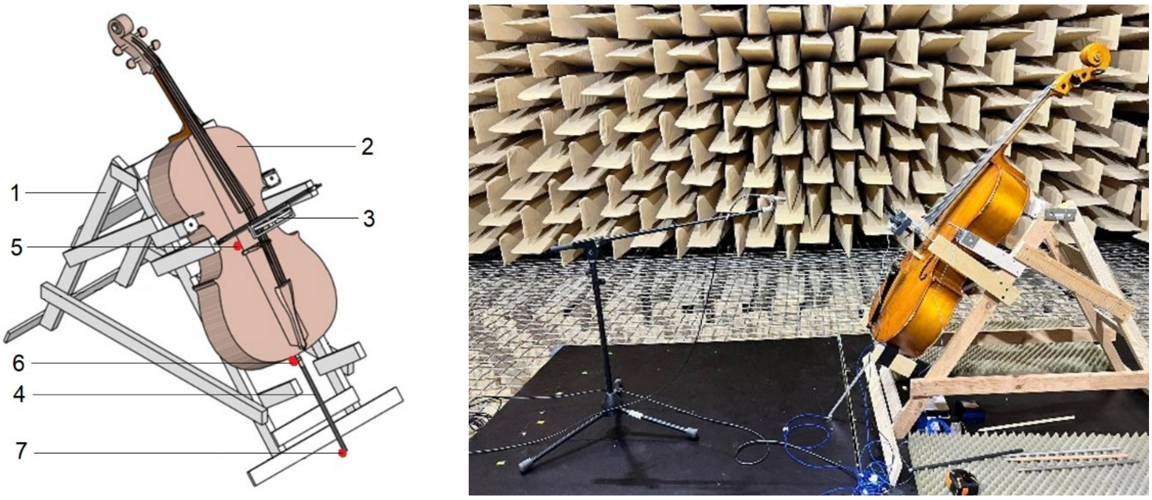


Figure 4. Measurement setup: 1 – wooden frame, 2 – cello, 3 – sound generating mechanism, 4 – cello endpin, 5, 6, 7 – location of vibration sensors (red dot).

Measurements were made using a microphone and three vibration sensors. Detailed information about the measuring equipment is provided below:

- vibration sensor model 352C33 / sensitivity 100.3 mV/g (at endpin on the floor)
- vibration sensor model 352C33 / sensitivity 100.2 mV/g (at the endpin hole)
- vibration sensor model 352C22 / sensitivity 10.5 mV/g (between f-holes)
- microphone G.R.A.S 46AE (at a height of 0.87 m at a distance of 0.5 m from the neck)
- measurement module SV 06A
- a computer with an audio interface

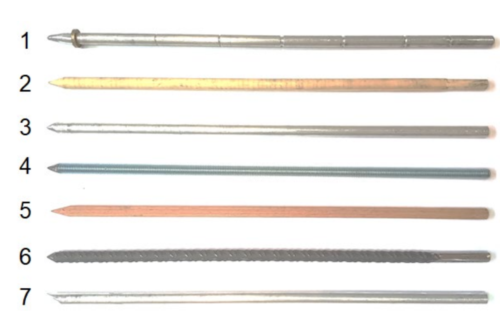
The measuring microphone was placed 0.5 m from the neck at a height of 0.87 m in front of the resonance holes (f-holes). Sensors and a microphone were connected to the measurement module SV 06A. 60-second waveforms were recorded on four tracks in Matlab software using the audio interface. There were seven repetitions for each string due to the type of material of endpins. After taking a series of measurements on one string, the wheel was moved slightly to the side so that it touched the string on which it should play in a given measurement. The frequency of the generated sound corresponded to the frequency of the open strings of a cello: C – 65,40 Hz, G – 97,99 Hz, D – 146,83 Hz, A – 220,00 Hz. Measurements were made using each of open string.

The contact between the wheel and the strings could also be adjusted with screw nuts (Fig. 2, item 9). The pressure on the strings was regulated by tightening or loosening the screw nuts on the threaded pins on both sides of the wooden frame. It was important that the once established pressure, remained the same throughout all repetitions on the same string. In order to maintain the repeatability of the excitation, the endpins were replaced by lifting the wooden frame (with the cello), which was hinged to the ground.

4.1. Types of cello endpin materials

Several decades ago, the cello's endpin was treated only as an element supporting the instrument on the floor. Recently, due to the variety of materials used for cello pins, started to be discussed about the influence of these materials on the cello sound. Seven types of materials from which the cello endpin was made were analyzed (Tab. 1). Three endpins made of aluminum were used for the measurements – a regular rod, a hollow rod and an original cello endpin. Aluminum is one of the most popular materials, it is a soft and stretchy material, but it is characterized by low material strength. The next two legs are made of wood – beech and pine. Beech is a harder wood than pine. They were used for research, due to the history of the instrument – in the Baroque period, the cello had a wooden one. The lengths of all the endpins were equal and amounted to 0,4 m and the diameters were 0.01 m. The most important material parameters are presented below (Tab. 1).

Table 1. Types of cello endpin materials.

	No.	Material	Density [kg/m^3]	Mass [g]
	1	original endpin (aluminum)	2700	83
	2	pine	700	18
	3	rod (aluminum)	2700	81
	4	threaded pin	7500	150
	5	beech	690	22
	6	rebar	7900	238
	7	hollow rod (aluminium)	2700	28

5. Analysis of the timbre of the cello sound

The timbre of sound is a subjective quality of sound. It allows to distinguish the sounds of different instruments, even if they have the same base tone frequency. The sound of an instrument is affected by many factors and elements related to the construction of the instrument. The timbre of the sound depends on the spectral composition of the acoustic signal, the proportion of harmonic frequencies and the envelope of the signal's time waveform. A sound that contains few high frequencies can be described as "dark" or "deaf". The predominance of higher frequencies makes the sound more glassy/metallic. The timbre of the sound is also affected by the phases that can be distinguished in the signal envelope: attack, decay, sustain and release time. The conducted analysis focused mainly on the analysis of the spectrum and the sound pressure level. The analysis of the discrete signal in the frequency domain was performed by calculating the discrete Fourier transform expressed by the formula:

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{\frac{-i2\pi kn}{N}} \tag{3}$$

where i – imaginary unit, $k = 0,1,\dots,N-1$ – harmonic number, n – signal sample number, $x(n)$ – signal sample value, N – number of samples.

Based on the frequency distribution in the spectrum and their amplitudes, the spectral centroid was also determined according to the formula (4). In the case of complex tones, the spectral centroid is higher when the tones have more energy (amplitudes) in higher component parts. Therefore, the spectral centroid is an indicator of the richness or brightness of a sound [11]:

$$C_i = \frac{\sum_{n=0}^{N-1} f(n) X(n)}{\sum_{n=0}^{N-1} X(n)} \tag{4}$$

where C_i – centroid [Hz], $f(n)$ – frequency [Hz], $X(n)$ – amplitude [-].

Subjective research on the influence of the cello endpin material on the timbre was carried out on a group of 5 professional cellists. The musician played the same fragment of a piece of music with an endpin made of three different materials. The cellists determined on a scale from 1 to 5, based only on the listening impressions of musical fragment played by the cellist (the signal was not recorded), whether the timbre of the instrument was darker or brighter, depending on the type of tip used. All subjective tests were carried out in the same rehearsal room – the results are presented for comparison purposes only.

6. Results and analysis

The difference in the measured sound pressure level generated when the mechanism is working but without generating sound (no contact between the wheel and the cello string) in relation to the working mechanism generating the sound is 20dB. It can therefore be assumed that the working mechanism did not significantly affect the measurement results. The sound generated by the mechanism is more stable in the time waveform signal than when played with a bow. An example of the time waveform signal of tone A is shown in Fig. 5. About 5 seconds of the signal duration, a change the bow direction is clearly visible (Fig. 5a). For the other frequencies, the differences in the time course of the recorded signals are similar.

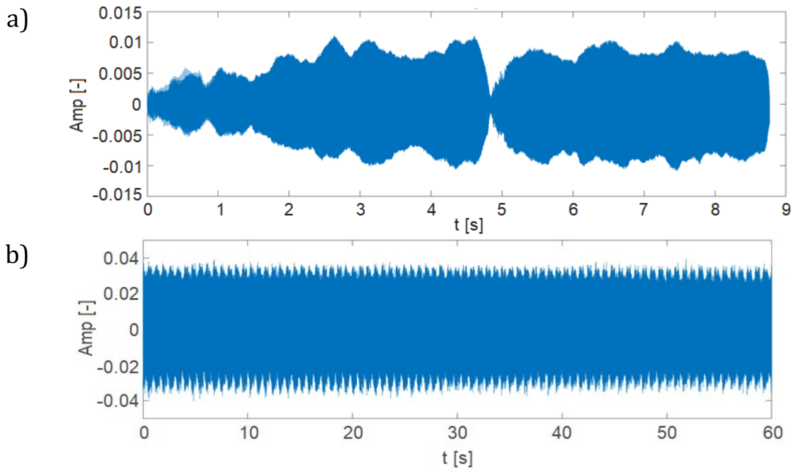


Figure 5. Waveform of the microphone signal in the time domain of tone A; a) – using bow, b) – using mechanism.

The analysis of the centroid value from the vibration sensor located on the body between the resonance holes (f-holes) showed that the change in the material of the endpin does not significantly affect the vibrations in this place. The greatest impact of changing the material of the endpin can be seen for the sensor located on the ground and the signals recorded by the microphone. Exemplary results for the types of endpin for which the differences of spectral centroid were the greatest for the lowest and highest of the analysed frequencies (tone A and C) were presented (Fig 6-7).

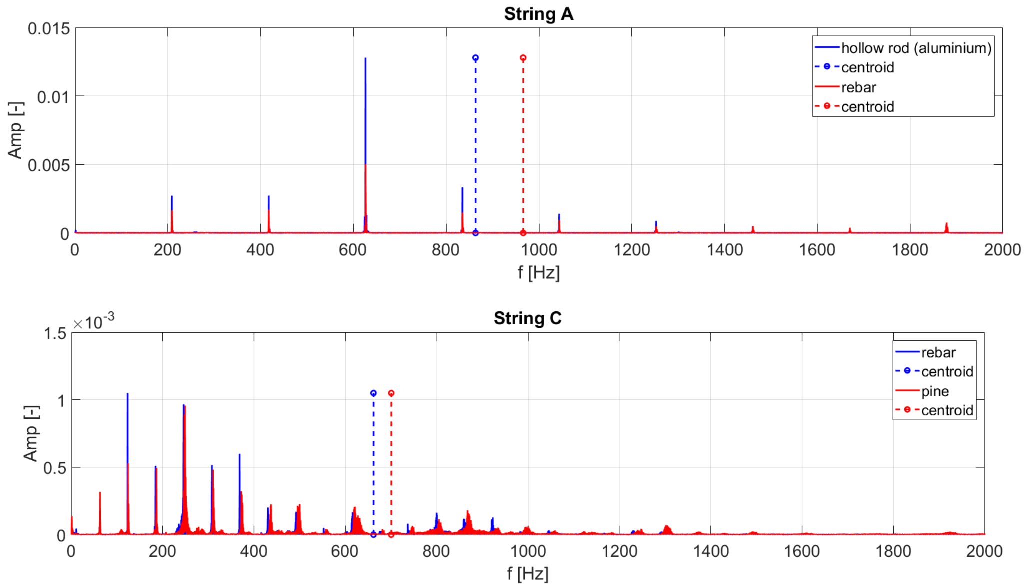


Figure 6. The results of sound spectrum measurements for the highest (tone A) and lowest (tone C) analysed frequency.

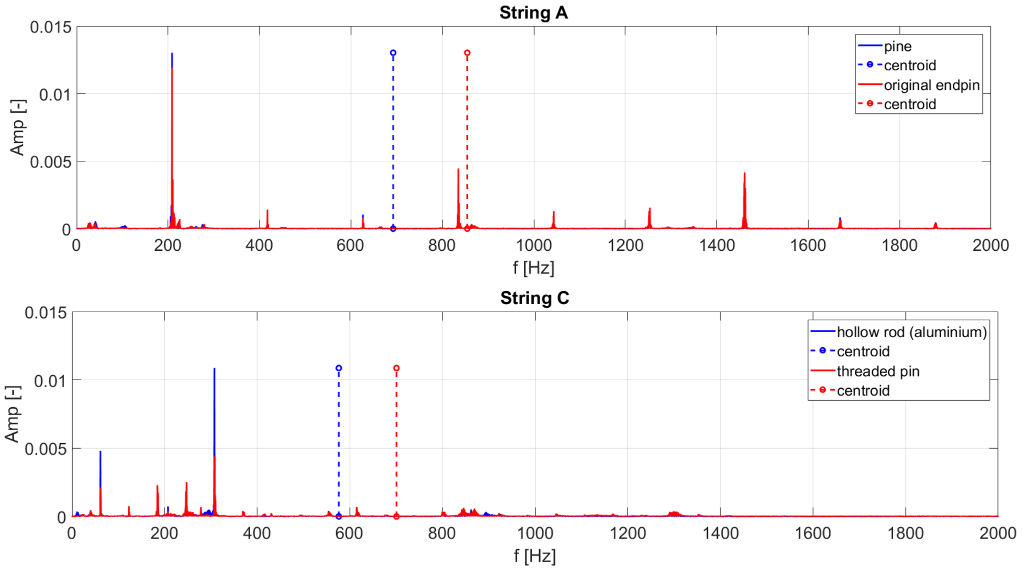


Figure 7. The results of vibration acceleration spectrum measurements (sensor on the ground next to the endpin) for the highest (tone A) and lowest (tone C) analysed frequency.

In the case of the sound spectrum of the A string, the difference between the extreme values of the centroids determined for different endpin materials is 102.6 Hz. And for the sound spectrum of the C string – 30.1 Hz. The differences in the extreme values of the centroids for the vibration sensor placed on the ground are 162 Hz for the A string and 124.4 Hz for the C string.

Below are graphs (Fig. 8) of subjective impressions of sound brightness for three cello endpin materials. Three types of endpins made of beech, rebar steel and aluminium were tested. These endpins are the most varied in terms of physical parameters, which can be included in the group of materials made of wood, steel and aluminium. During the subjective tests, the cellist played a fragment of a piece of music, so the pitch of the generated tone varied.

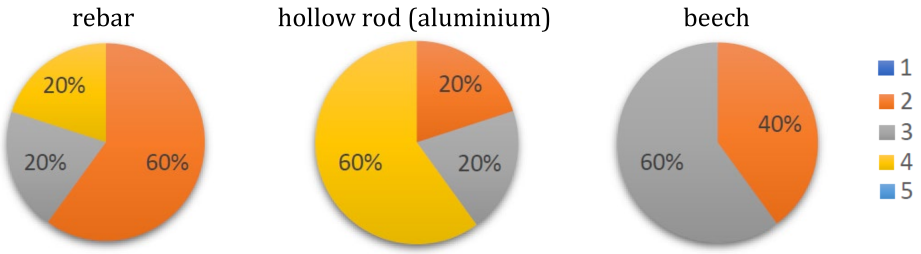


Figure 8. The results of the subjective impressions of the musicians determining the brightness of the timbre on a scale of 1 to 5 (5 - means bright, 1 - means dark).

The musicians pointed out that the sound of a cello with an endpin made of rebar is darker than in the case of an endpin made of beech, and even more so aluminium. A subjective test was carried out on a small number of cellists but it allowed to determine the trend related to the influence of the cello endpin material on the cello's timbre.

7. Conclusions

The purpose of this work is to present the construction of a mechanism for generating a continuous cello sound. The application of the designed device in the preliminary studies of the influence of the cello endpin material on the timbre of the instrument is presented. Such a device can be useful in performing research related to the timbre of string instruments where repeatability of the generated sound is required. Based on the spectral analysis and centroid, the influence of the endpin's material on the timbre of the instrument was demonstrated. However, the results of vibroacoustic tests do not clearly coincide with the subjective impressions of cello musicians professionally playing the cello, a certain tendency can be noticed that the use of a cello endpin with a higher density material results in a darker timbre of the instrument in the low frequency range. There are many factors affecting the sound of instruments, therefore vibroacoustic tests of elements affecting the timbre require a detailed analysis. In addition to the material of the endpin, the material and geometry of the podium on which the endpin is based are very important. Thanks to a properly designed structure, for example, determining the natural frequency of the leg-podium system, some frequencies of vibration transmitted through the endpin can be additionally strengthened by the podium. The presented research results may be helpful in the selection of materials for the construction of the cello endpin. Further research may be used to formulate guidelines regarding the most favourable material for the construction of the substrate on which the cello is placed. Measurements on the presented setup should be carried out, paying special attention to the stabilization of the cello in the wooden frame during the replacement of the endpin in order to maintain the repeatability of the generated sound.

Additional information

The author(s) 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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