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The bowed string instruments: acoustic characterization of unique pieces from the Italian lutherie

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Abstract. The Italian handicraft tradition in the construction of bowed string instruments is a very important element of the Italian cultural heritage, that has nothing to envy to other well-known traditions, such as painting and sculpture. The preservation of a handicraft musical instrument is fully incorporated in the preservation of the artworks of Italian heritage. In order to ensure suitable preservation, the systematic studies for the determination of the technical and acoustic characteristics of handicraft musical instruments are of particular interest. This study deals with the characterization of the bowed string instruments, with a particular attention to their acoustic behaviour. The idea of conducting such a research arises from the need to describe a systematic process aimed at the characterization of handicraft instruments and to collect in a single survey a description of different pieces from the Italian lutherie.

1. Introduction

The bowed string instruments owe their name to the fact that the sound is produced by rubbing the strings by means of horsehair stretched on a bow. The violin family as we know it today (violin, viola, cello and double bass) draws its origins from the oldest *viola da braccio*, an instrument with four strings tuned in fifths, and the *viola da gamba*, whose features remain mainly in reference to the handling position in the cello and the double bass [1-5]. Although different in size, the four components of the violin family consist of the same acoustic chain arranged in three groups (Fig. 1): 1- top plate, back plate and ribs; 2- top nut, tailpiece, bridge, scroll and strings; 3- sound post and bass bar. The representative of the bowed string instruments is historically the violin, invented by *Gasparo da Salò*, whose construction peak has been reached with the Cremona lutherie school with *Nicola Amati*, his pupil *Antonio Stradivari*, and others [1,4-7]. The realization of a violin involves the adoption of about 64 pieces; the operative mode, ranging from choosing the material to the recording of the instrument, is essential for the good quality of the violin itself. As a 'prince' of the bowed string instruments, the violin is the one of which the literature on acoustics mostly deals [8-15]. Viola, cello and double bass differ from the violin in terms of size and tuning, while the mechanisms of sound production are common: this makes that the results found for the violin can be easily extended to the other members of the bows family. However, the absence of a precise search for these instruments involves the lack of an acoustic optimization, especially with regard to low registers; what is mostly affected is the timbre of the instrument, significantly different from that of the violin.

This study deals with the characterization of the bowed string instruments, with a particular attention to their acoustic behaviour. The idea of conducting such a research arises from the need to describe a systematic process aimed at the characterization of handicraft instruments and to collect in a single survey a description of different pieces from the Italian lutherie. That process consists of a harmonic analysis and a temporal pattern analysis. In order to carry out a significant investigation, reference was made to the following unique pieces of Italian lutherie: a *Bernardini* violin (2006), a *Bernardini* viola (2010), a *Carletti* cello (1910) and a *Verdiani* double bass (2000). The conducted analyses enabled the processing of graphs, such as the frequency spectrum, which allowed to identify the main acoustic characteristics of the instruments, as well as to capture the differences. At the same time, it was also conducted the analysis of data and diagrams already in literature, searching for a direct comparison with the musical instruments used and having, in this way, a global view of the characteristics of the bowed string instruments.

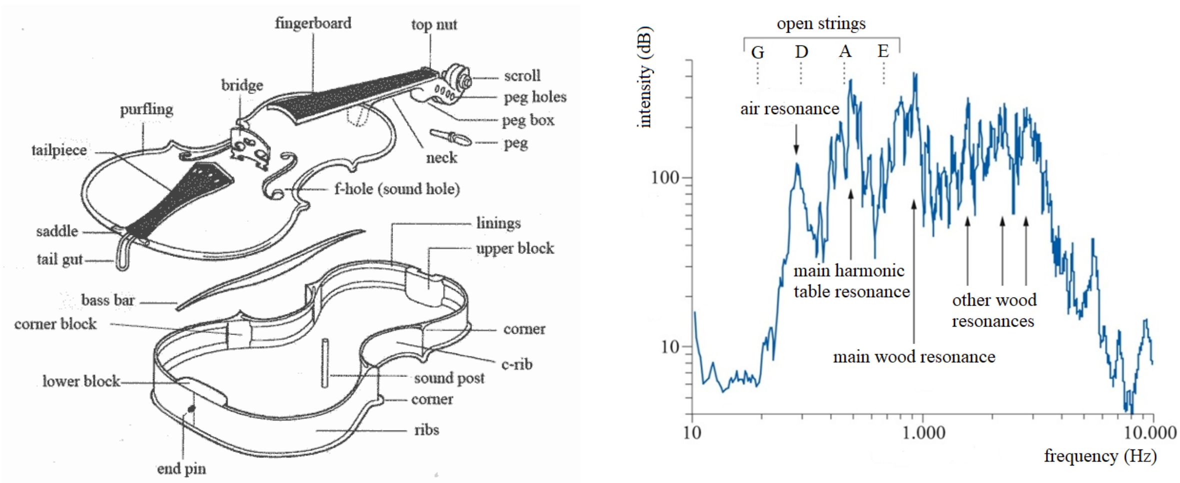


Figure 1. Components of a bowed string instrument (left); example of a sound spectrum of a violin (right).

2. Acoustic analysis of musical instruments: the ADSR envelope

The study of the acoustic characteristics of a musical instrument can be differentiated in two phases: the first is the one of harmonic analysis and is conducted by identifying a graph (the sound spectrum, e.g. Fig. 1) that returns the sound intensity (dB) according to the frequency (Hz); the second is the one that studies the time proceeding of sound by defining the ADSR envelope (Attack-Decay-Sustain-Release, e.g. Figs. 3-6), tracing the sound amplitude according to time. Both types of analysis are very important for a complete acoustic characterization of the various musical instruments. In this way, each instrument is unequivocally defined in order to make it recognizable even within large formations such as bands and orchestras.

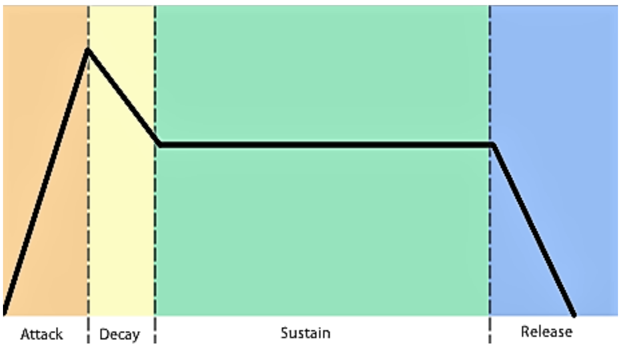
With the expression ‘envelope of the sound’, is intended the timing of the magnitude of sound from the moment it is generated until it extinguishes. Each sound has its own dynamic evolution: there are sounds, such as the ones generated from percussion and piano, which have a flash attack, others, such as flute or violin, which have a sweeter and more gradual attack. Some sounds can be kept as long as the performer wants it (in the case of the violin this aspect is governed by the use of the bow, in the case of the flute instead of the musician’s breath), while others disappear in more or less time without the performer may have a decisive influence on their behaviour. Generally, it is possible to say that all sounds start from a zero volume, they reach the maximum volume and then, after a time-varying evolution, they return to zero. In the case of the violin, and more generally of the bowed string instruments, execution is essential for the determination of the sound envelope: the notes may have an initial peak, or reach a maximum at the end, or maintain a constant volume without no peak in particular according to the will and needs of the musician.

These facts can be summarized saying that musical instruments are distinguished in two great classes that exhibit a very different sound envelope behaviour:

- ‘free evolution’ instruments, instruments in which the performer is limited to providing initial energy, and can not intervene significantly to influence the dynamic evolution of sound that gradually decreases until extinction (this category includes string instruments such as harp, guitar, lute, harpsichord, instruments with percussion strings such as the piano and percussions);
- ‘controlled evolution’ instruments, the performer provides energy continuously to maintain sound, when the performer ceases to power, the sound disappears more or less quickly (artificial instruments, wind instruments, voice, organs are part of this category).

It is now possible to define the dynamic variation of a sound over time as the set of four distinct phases articulated in the ADSR envelope (Tab. 1). It is important to point out that the four phases of enveloping are such a sketch of what is happening in reality, useful in studying the dynamic evolution of sounds. Also in the sustaining phase the sound is never perfectly firm (it would not be human) also because of executive practices such as vibrato or double strings of bowed string instruments. With regard to the specific case of bowed instruments, the ADSR diagram is generally found to be devoid of the decay phase, as the amplitude of the sound grows rapidly with the bow movement and reaches an uncontrolled sustain state. The performer can, however, change the trend of the envelope by inserting a decay phase with the execution of a *sforzato*, that is an accented sound for which, once the maximum volume has been reached, there is an initial decay followed by holding on a smaller volume.

Table 1. Sketch of an ADSR envelope and description of the four phases.

Sketch of an ADSR envelope	Phase	Description
	**Attack**	The phase from the moment in which the sound is generated until it reaches its maximum intensity; the beginning of the sound can be immediate (in the case of a piano or a percussion instrument this takes around 1/100 sec) or gradual (in the bowed and wind instruments the performer can create an attack in *crescendo* of the duration of various seconds).
	Decay	The short and rapid decrease in amplitude after the attack, which precedes the sound stabilization (also referred to as initial decay or first decay); this stage may also be completely missing to leave the place directly to the sustain phase.
	Sustain	The phase where the sound stays stable while the performer continues to provide energy; during the sustained phase the sound intensity does not undergo any major changes, remaining almost constant.
	Release	The phase that begins when the performer stops delivering energy and the sound declines more or less quickly (also known as the final decay), it is then shifted from the constant sound intensity of the sustain phase to a lower intensity even to the background noise; this stage can also be very long in free-evolving instruments, while it is usually short in the controlled-evolving ones.

3. Sampling of bowed string instruments

The interesting aspect of this work has been to analyse the results obtained by sampling the bowed string instruments. These have been sampled using the Cool Edit Pro 2.0 software, with the conduction of two types of analysis: with the former it has been obtained the acoustic spectrum of the four instruments; with the second one it has been evaluated the ADSR envelope of the four notes corresponding to the open strings of each instrument. The acoustic spectrum was obtained by playing *glissando* (that in music represents a glide from one pitch to another) on the four strings of the various instruments. The *glissando* was played by a professional musician. Through the Fourier analysis, the software returned the sound amplitude distribution in function of the frequencies emitted. The ADSR envelope was instead evaluated by playing the four open strings of each instrument individually. The results obtained for violin, viola, cello and double bass are reported. Finally, it is necessary to specify that the data collected are not to be considered as absolutely valid, but only about the instruments used in this particular survey and therefore related to the particular constructive features of them. The experimental characterization has been done in a special room, quite similar to a hemi-anechoic chamber, realized in the Bernardini Lutherie headquarter, being negligible the background noise level.

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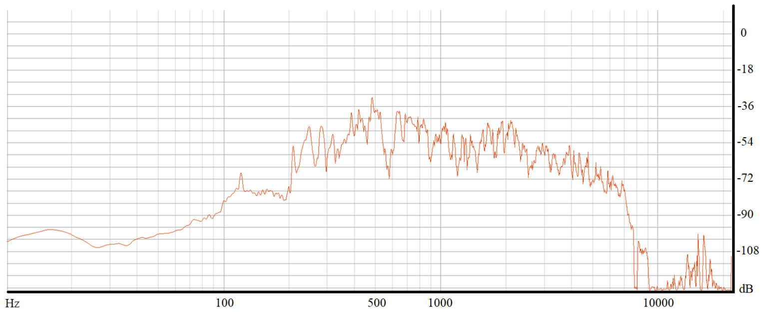

Figure 2a.
Bernardini violin

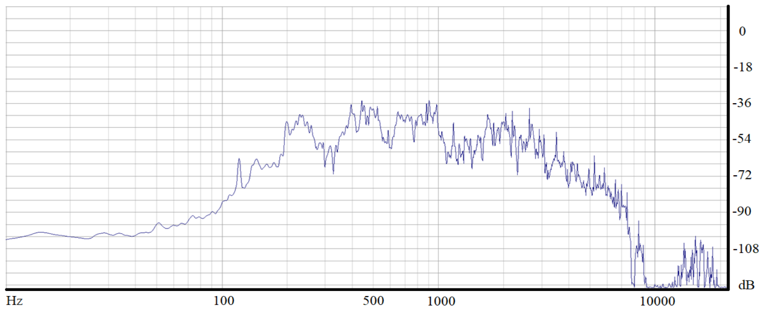

Figure 2b.
Bernardini viola

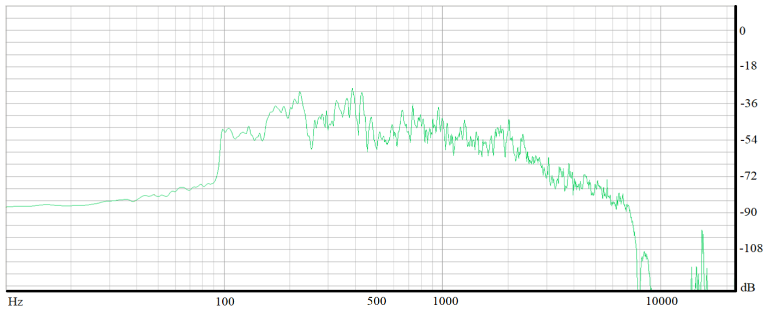

Figure 2c.
Carletti cello

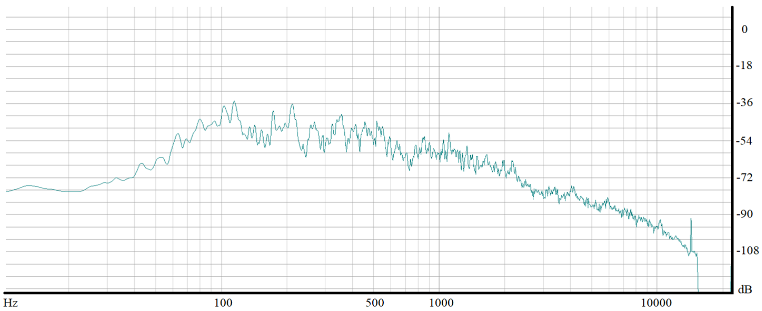

Figure 2d.
Verdiani double bass

Note that the scale of intensity in the vertical axes returns negative values, characteristic of the particular mode of calculating decibel levels (logarithm of the relationship between a certain value and a value taken as a reference).

Figure 2. Acoustic spectra of the four bowed string instruments: (a) *Bernardini* violin, (b) *Bernardini* viola, (c) *Carletti* cello, (d) *Verdiani* double bass.

3.1 Violin

The measurements were conducted on a *Bernardini* violin of 2006. The frequencies commonly issued by a violin, taking into account only the fundamental notes, have lower and higher extremes of 196 Hz (G3) and 3136 Hz (G7); if we also consider the frequencies emitted by artificial harmonics then the field should be extended to more than 5000 Hz. As can be seen in Fig. 2a, the acoustic spectrum of a violin detected by the software occupies a much wider range than the one just quoted; whereas some peaks are also due to the presence of noises, such as strings rubbing or vibration of instrument parts, we can speak of a frequency range of approximately 60 Hz to more than 15000 Hz. The cause of this greater amplitude in the range of emissions is to be sought, of course, in the presence of natural harmonics from which one can not discern in the acoustic evaluation of an instrument (a violin is all the more rich and sonorous as many natural harmonics is able to emit). From the analysis of the spectrum of the violin considered there is a good correspondence with the spectra in the literature: the instrument has the maximum emission amplitude at 500 Hz (resonance of the harmonic table), maintaining a good sound intensity between 300 Hz and 2000 Hz. Before and after the maximum emission, there is a minimum of sound intensity: this is justified by the fact that at resonance the sound waves are of a constructive nature, therefore they must be preceded (and succeeded) by waves of destructive type; this is the case of the sound wave in phase and out of phase. After the sound spectrum and spectrograms analysis (not showed in this paper for the sake of simplicity), the ADSR envelopes were identified. This analysis was once again conducted for the notes produced by the four open string of the instrument: G_3 (196 Hz), D_4 (294 Hz), A_4 (440 Hz) and E_5 (660 Hz). In the graphs obtained through the Cool Edit Pro 2.0 software (Fig. 3), there are two coloured lines that approximate the envelope in a very schematic way: in particular, with the blue line (bottom line in the Fig. 3) it was attempted to follow more precisely the software redraw, with the orange line (top line in the Fig. 3) it was attempted to create an analogy with the standard lines with the ones that theoretically describe envelopes of this type. Note that only in the case of A and E notes the two approximations are almost coincident: for these two notes, therefore, the subdivision into the phases of Attack, Decay, Sustain and Release are fully recognizable; for the notes of G and D the trends of the two coloured lines do not coincide, emphasizing that the division into four phases is not always present in the envelopes of the notes emitted by the instruments. It is important to recall that the subdivision in four phases is a mere simplification to understand how the sound emission of the instruments works and how they produce sounds in a very different physical mode; it is not to be understood as a precise description of the physical phenomenon itself.

3.2 Viola

The instrument analysed in this case is a viola *Bernardini* of 2011, whose acoustic spectrum is reported in Figure 2b. It is still a quite uniform distribution in the range of frequencies that for this instrument has as extremes, referring to the fundamental notes, 131 Hz (C_3) and 1174 Hz (D_5); the forming frequency are those from 450 Hz to 1000 Hz. Anyway, as in the case of the violin, is from frequencies around 40 Hz to more than 10000 Hz. The analysis of the envelopes of notes corresponding to the open strings of the viola (Fig. 4) points out an aspect that has already been mentioned at the beginning of this paragraph and that has already found in the case of the violin. The four phases recognized in Attack, Decay, Sustain and Release are not always present or recognizable; especially in these measurements, the Decay phase was not detected for any of the four notes. Therefore, it was not possible to return the simplified blue line to the standardized one (orange line in violin envelopes, see Fig. 3). Notice how the sound attack is almost immediate and the release is very late in all four cases.

3.3 Cello

Measurements for the cello were performed on a *Carletti* instrument of 1910. The frequency range usually emitted, in relation to the fundamental notes, is recognized between about 65 Hz and 988 Hz. As it can be seen from Fig. 2c, the range of frequencies emitted is larger than the one just mentioned: this is due to the fact that the analysis software considers also the harmonics emitted by the instrument, such as in the cases of violin and viola. By comparing this spectrum with the ones of the violin and viola, it is obvious that in this case the decibel levels are lower and the sounds tend to extinguish below 10000 Hz. The instrument resonates at 400 Hz, reaching its highest sound level of -28 dB; before and after the resonance peak, there is an immediate decrease in the sound level, justified by the fact that the sound waves are out of phase. The cello has the same tuning of the viola, but at a lower octave; we therefore expect a greater concentration of harmonics at lower frequencies than those of viola and violin. The analysis of the envelopes for the notes corresponding to the cello open strings

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(Fig. 5) show what has already been seen for the viola: in fact, even in this case, the four phases recognized in Attack, Decay, Sustain and Release are not always present or recognizable; only in the case of the A open string it was possible to refer the blue line characteristic of the note to the standardized line in orange, recognizing the presence of all four phases of the envelope. For the open string of C, G and D, this reconnaissance was not possible. Notice how the sound attack is almost immediate and the release is very late in all four cases.

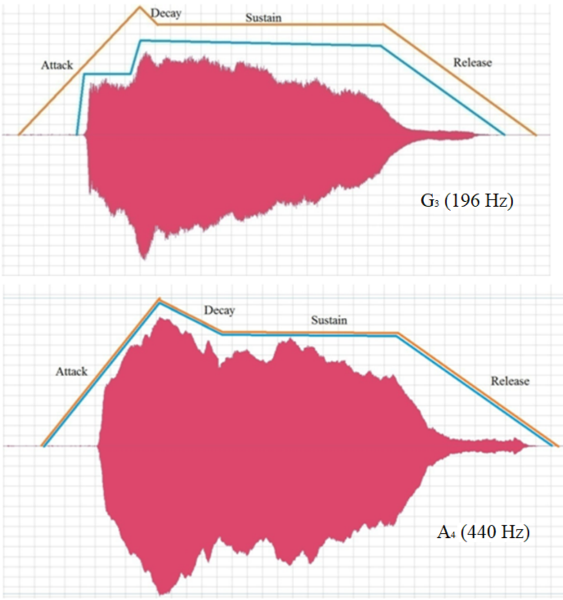

Figure 3. *Bernardini* violin (2006) open strings ADSR envelopes for fundamental notes of: 196 Hz (left, top), 294 Hz (right, top), 440 Hz (left, bottom), 660 Hz (right, bottom).

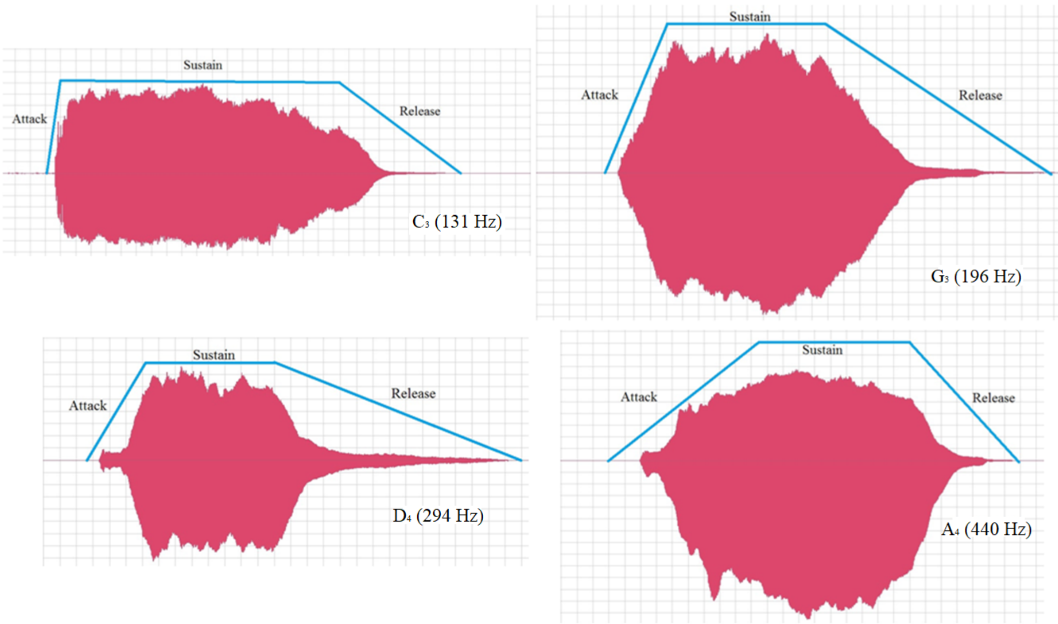

Figure 4. *Bernardini* viola (2011) open strings ADSR envelopes for fundamental notes of: 131 Hz (left, top), 196 Hz (right, top), 294 Hz (left, bottom), 440 Hz (right, bottom).

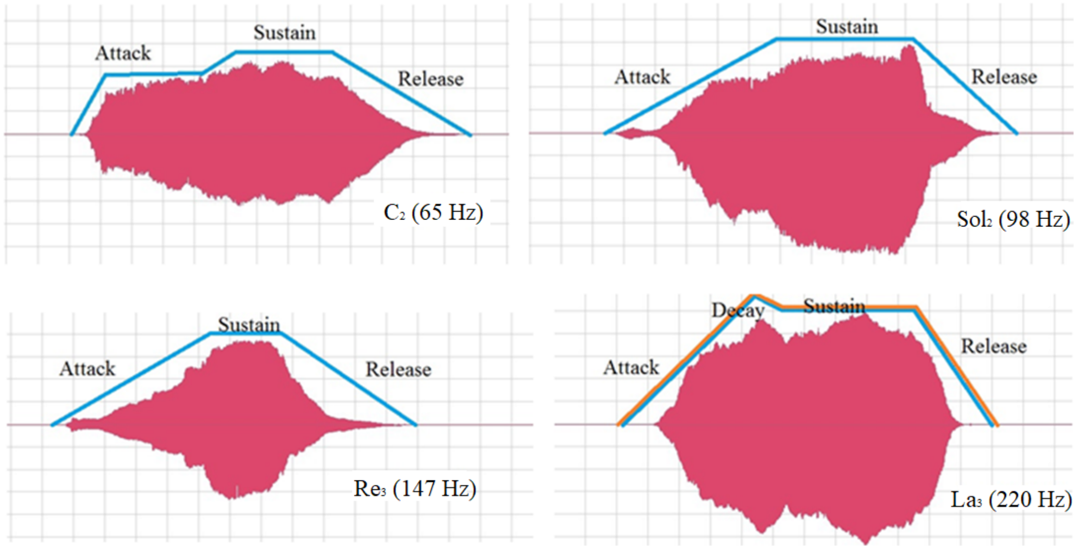

Figure 5. *Carletti* cello (1910) open strings ADSR envelopes for fundamental notes of: 65 Hz (left, top), 98 Hz (right, top), 147 Hz (left, bottom), 220 Hz (right, bottom).

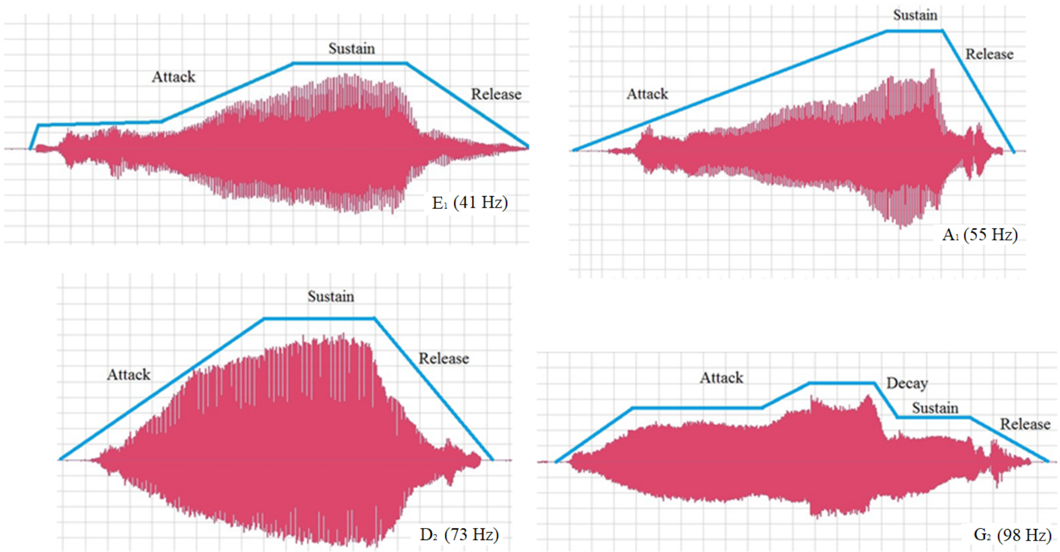

Figure 6. *Verdiani* double bass (2000) open strings ADSR envelopes for fundamental notes of: 41 Hz (left, top), 55 Hz (right, top), 73 Hz (left, bottom), 98 Hz (right, bottom).

3.4 Double bass

The double bass used is a *Verdiani* instrument of 2000. The particular double bass feature, in addition to having retained constructive traits typical of the *viola da gamba*, is that it has a different tuning compared to the others bowed string instruments. In fact, while violin, viola and cello are all tuned in fifth intervals, the double bass shows a fourth tuning; the succession of open strings, therefore, starting from the lowest note to the highest, is E, A, D and G. From a first analysis of the acoustic spectrum of the double bass shown in Figure 2d it can be observed that this does not reach the sound intensity levels detected for the other instruments: the highest level only stands at -36 dB at the frequency of 120 Hz while, for frequencies between 400 and 1000 Hz, where violin, viola and cello had resonance peaks at least -35 dB, the double bass shows an emission even below -45 dB. Even in the case of the double bass it is possible to consider a spectrum of emission larger than the one generally recognized in the literature, essentially between 41 Hz and 247 Hz. Taking into account of natural and artificial harmonics, it is legitimate to consider a spectrum of emission that starts from about 40 Hz and reaches at least 1000 Hz, although with very low intensity. Acoustic spectrum (and spectrograms) justifies the particularly gloomy nature of the double bass and the difficulty often encountered by luthiers in making instruments that have a full, clear and intense sound. The double bass study is also completed by the determination of the ADSR envelopes obtained once again for the open strings of the instrument (Fig. 6). As in the case of the viola, it was not possible to recognize in the envelopes founded the standard form, confirming again that the theoretical proposal respects the real situation only in some cases. In most cases, the phase division of Attack, Decay, Sustain and Release takes on various shapes and is not always present. For the double bass, the only one of the open string to present a four-phase subdivision is the one of G.

4. Conclusive remarks

The study of this limited number of instruments let us already understand that the family of the bowed string instruments is acoustically enough homogeneous, but at the same time is characterized by very different textures. These peculiarities are undoubtedly the ones that over the centuries have given these instruments a special attention by the composers, who have entrusted them with the most varied roles, from brilliant solos to orchestral filling. It is also clear how difficult it is to define the standards that characterize violin family in an objective way: the different types of wood used for their construction, the realization techniques of the various luthier schools, the real dimensions, the thicknesses of the various elements, they are all characteristics which give a certain degree of randomness in the acoustic behaviour of these instruments. That's why musicians often have to look for their ideal instrument for years to find the one that best suits their needs and that best suits their way of playing: they can not trust in a simple physical description of it, because it would not be able to fully represent its potential.

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