Contribution Of the Cello Tailpiece To the Overall Tone

The Material

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31/05/2021
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Summary :

The choice of setting up a tailpiece on a cello gives very different results in the sound. It can affect the balance or richness of tone, as well as the ease of sound emission.
Understanding the contribution of the tailpiece to the overall tone is the first goal of this study, and as a result, it helps the luthier in his choice of set-up, and to optimize the instrument.

We compared several set-up, changing only the wood of the tailpiece. After a qualitative study of the perception of the sound of the instrument, we looked for a link with acoustic measurements.
The recording of a scale for each tailpiece set-up allowed the study of the time envelope, the sound spectrum of the instrument, and the spectrum of the tailpiece vibrations.

Finally, the modal analysis of each tailpiece made it possible to specify the mechanical behavior of their own resonances, as well as the values of the dynamic markers which are the modulus of elasticity and the Quality factor linked to sound damping.

Correlations appeared between the perceptual sound classification of these assemblies, and the mechanical qualities of the wood species used.
The choice of the tailpiece, made by the luthier, can thus be guided by using the preliminary study of its properties.

Introduction

Perceptional study of 8 successive tailpiece set-up, on a Mittenwald Cello, allows us to discover sound differences, due only to the change in the species used for the tailpiece.

The action of the string by the bow is first communicated to the bridge, whose feet transmit vibrations to the body of the instrument. The body and the front will then emit an audible sound.

The vibration of the strings is also communicated to the body of the instrument through the bottom nut, passing through the tailpiece. The size of the latter is insufficient to emit a sound, but it will filter the vibrations transmitted, and thus contribute to the overall sound of the instrument.

In the ***acoustic study*** presented here, each set-up was recorded on two channels:

- one recording by a microphone, showing the sound perceived by our ears,
- and a second one, by an accelerometer placed on the tailpiece, which recorded the vibrations which goes through it.

The ***temporal envelope*** is the amplitude curve of the notes of a scale played. It shows an inequality of sound amplitudes from one note to the next in the same set-up, but also other inequalities, for the same note, from one tailpiece set-up to another.

When listening, these differences are not perceived as variations in power, but as changes in tone.

Spectrographic analysis allows each note to be split into its harmonic components,
- with the sonogram,
- then the spectrogram.

The study of the aerial sound recording, by the microphone, does not show many differences between the different assemblies

We were particularly interested in the other way recorded with the accelerometer, that of tailpiece vibrations.

Indeed, over the entire spectrum played, the curves highlight almost blank frequency bands, and other bands with boosted amplitude.

Some set-up have very uneven bands, other tailpieces are much more regular.

The breadth, and the number of these bands is correlated with the perceived sound quality of the instrument: the more "blank" bands there are, the less set-up of this tailpiece is appreciated.

The "boosted" frequencies are often the same for the whole range of a given set-up, and suggest their coupling (a sympathetic resonance) with resonance modes proper to the cello body, but also to the tailpiece. We therefore studied the possible influence of these modes on the tone.

Modal Analysis

Any object,… here the tailpiece, reacts to preferential resonant frequencies, it has its own modal signature. It can resonate in sympathy when a corresponding note is played, and interact with it.

Thus, the vibratory transmission between two objects, as here between the tailpiece and the resonance chamber, can be filtered, altered or amplified by this coupling.

For each set-up studied, we determined the resonance modes of each tailpiece in three situations: as an individual object (Free-free), then as a connected object, in tension as on a silent cello, on a "dead rig", (devoid of sound box, and finally, set-up on the cello studied.

We see that the first resonance peaks of a tailpiece correspond to the same reinforced frequency bands on the sonogram and on the spectrogram. Conversely, the amplitude troughs between these resonance peaks correspond to diminished vibration bands of the spectrogram.

There is therefore a correlation between the natural frequencies of the tailpiece, and the tone result.

The more powerful and well separated the resonance peaks of the tailpiece, the more uneven the sound emission spectrum will be (frequent example : the boxwood tailpiece).

The more the peaks of the tailpiece are numerous, doubled, unequal, less powerful, the more the sound emission spectrum will be regular, and appreciated .

This study can be a starting point for other projects :

-What material for a tailpiece? What are the ideal qualities required for this acoustic filter.

-What is the influence of the assembly: length, type and geometry of the tailgut materials, which also modify the vibratory qualities transmitted by the tailpiece.

-Can we better understand the historical evolution of this accessory, during organological and technological modifications, and the evolution of musical tastes?

Plan :

PERCEPTIVE STUDY

Here, we're studying the perceived sound quality, on 8 identical set-up, except for the species of the wood. Each set-up was performed in front of a professional audience who gave a perceptual judgment.

All the tailpieces are of the same model, the same settings of the tailgut: First a tailpiece in Boxwood, then the next in Asian Paduk, another of the same species cut differently, Two tailpieces in Densified Spruce, one in African Paduk, then again the boxwood tailpiece tried in first position, and finally a last one in a closely related to Pernambuco wood from Mexico that we will call Mexican Pernambuco.

The sound perception of 8 Set-up:

	C300 Initial Boxwood	**C70 Paduk From Asia semi plain sawn**	**C71 Padouk From Asia plain sawn**	**C66 Densified spruce 1 by other maker**	**C68 Densified spruce 2 by Bois d'Harmonie**	**C231 Paduk from Cameroon**	**C300 Final Boxwood** (Played again after the experiment)	**C230 Mexican pernambuco**
Ranking for perception	+	++++++	+++++++	++	+++	+++++	++	++++
Tone	Quite balanced, Nice bass and treble, nasal medium	Balanced, equal, Rich tone	Even better balance, very nice bass, Thinner treble	Less interesting bass; Powerful treble, clear and bright.	Unbalanced colour and power, More opened sound	Balanced and focused tone; Nice bass, disappointing treble	Far better than first try; opened a bit; gained balance	Homogeneous; Pleasant tone, balanced, clean ; Some flaws on D string
Attack/Playability	Medium	Easy	Easy	Easy	Difficult	Easy	Easy	Easy
Power	Medium	Medium high A little decrease in the treble	Medium high	Less powerful	Medium high	Less powerful	Medium	More powerful than boxwood
*notes **Improve** perceptive studies criteria perceptive			A general index of the qualifying adjective should be clarified,including « famillies » of terms and their antonyms Bright/ precise./ focused; resonant/dry………. Would a criteria for "cleanliness" or precision be to be added?					

Listening to these 8 set-up, we noticed **a lot of sound differences**.

They **mainly** concern **differences in the timbre**, **homogeneity** of tone and **power**, as well as differences in the playability.

Human perception is not an objective tool, and we will be satisfied with a qualitative classification that we will compare with the physical measurements that follow.

This perceptual study certainly needs improvement. There is now an interesting bibliography on perceptual studies.
The C300 boxwood set-up, played at the beginning and then at the end of the manipulation, gave different results…

ACOUSTIC STUDY:

- We recorded scales with a microphone, sounds emitted in the air, those which reached our ears, for the analysis of the temporal envelope.
- At the same time, we recorded the vibrations passing through the tailpiece, with an accelerometer, which we will use for spectral analysis.

The tailpiece is too small to emit a sound in the air, it just transmits the vibration of the string to the amplifier: the body of the instrument.

The time envelope : Shows the amplitude of the vibrations over time

--- ***Uneveness from one tailpiece set-up to another:***

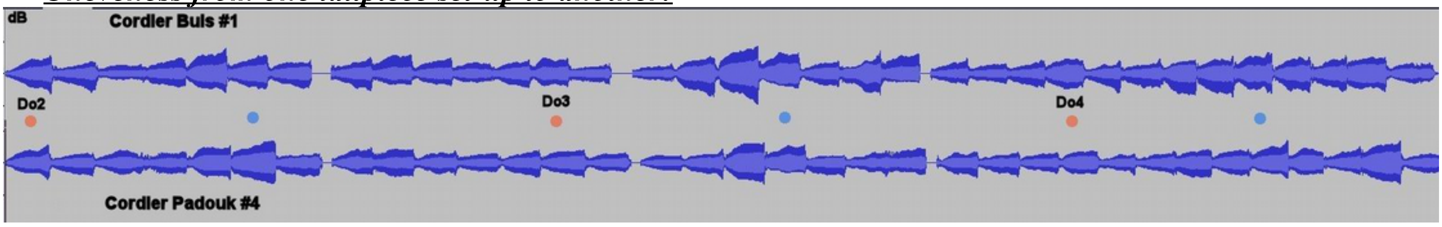


Fig1: Chromatic scale of 34 notes, for Boxwood # 1 and for Paduk # 4. Cs are underlined with a red dot, Fs with a blue dot.

The comparison of the envelope of the sound recorded for two set-up (fig1), shows an inequality of amplitude between the two. The Boxwood # 1 set-up is more irregular than the Padouk # 4 set-up.

You can notice differences in the amplitude of the same note, for example, a D, the third note on the left above, more "powerful" on the lower assembly. This difference in amplitude is not perceived when listening.

In sound perception, some set-up were qualified as more powerful than others, but we were unable to highlight a significant difference in overall amplitude level on these envelope curves.

---- ***Uneveness on the same set-up***: Inside the same set-up, there is also a strong irregularity from one note to the next.

In a scale, the envelope curve shows inequalities in amplitude, which we have not heard from listening. On the other hand, we have heard changes in tone.

Let us take as an example the difference between the two consecutive notes in figure 2. The increase in the amplitude of the C after the B (the thickness of the envelope), although visible in the figure on the left, is not perceived by the ear. It is due to the amplitude increase of a single harmonic, of 14 decibels, between the 3rd harmonic of the B at 370Hz and the 3rd harmonic of the C at 390Hz.

The variation in amplitude is not perceived as a variation in sound power, but as a change in timbre.

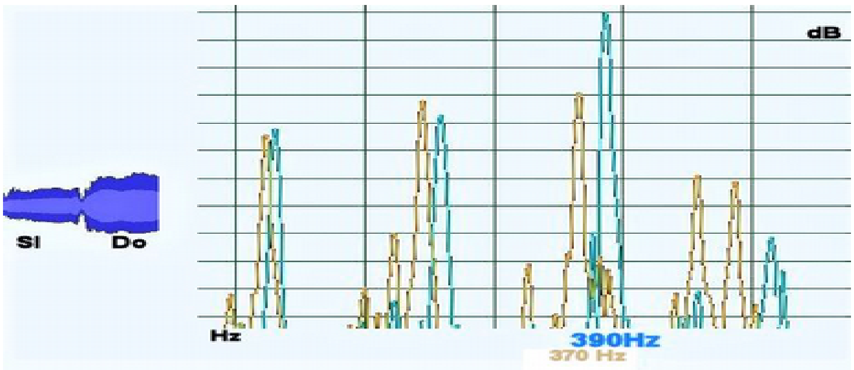


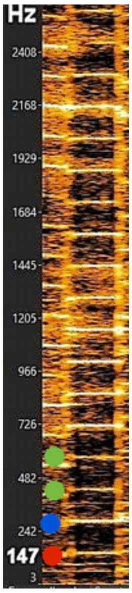
Fig2: C230 set-up on the left, time envelope of B2 and C3, and on the right, their harmonic spectrum. B in Yellow, C in Blue

The differences in the regularity of the amplitude from one set-up to another can be explained by the different mechanical qualities of the species used.

The differences in amplitude from one note to another in the same set-up can be explained by a difference in their harmonic composition. The hypothesis of harmonic couplings is considered below.

Finally, it should be noted that the human ear does not necessarily perceive the same amplitudes as the acoustic measurements.

The sonogram: **Shows the frequency of harmonics, and their intensity, over time.**

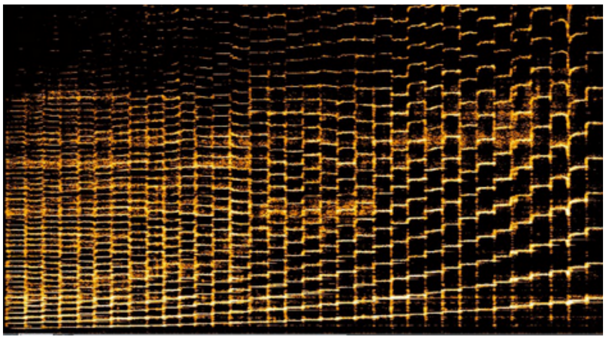


The sonogram splits a sound into its harmonic components.
Here, the D note breaks down into a fundamental note at 147 Hertz, represented by the first "bar" at the bottom of the scale. The 2nd harmonic is the next "bar", and so on.

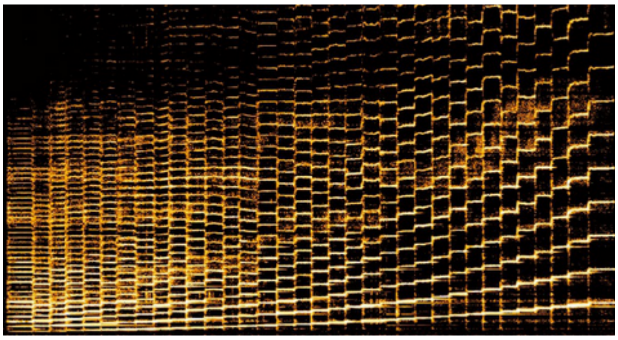
The intensity of the bar line represents the intensity of the Harmonic.
So, harmonic 2 is powerful, unlike No. 3 and 4, which are weaker in intensity.
The harmonic composition of a sound determines its timbre.

We compare the sonograms of the C300 tailpiece set-up (Boxwood), our worst perceptual choice (+), with the best choice, C71 tailpiece (Paduk), best tailpiece set-up (++++++)

1. **Sonogram of the perceptible sound**, microphone recording:



Sonogram of the radiated sound: Boxwood C300 setup



Paduk C71 set-up, Chromatic scale

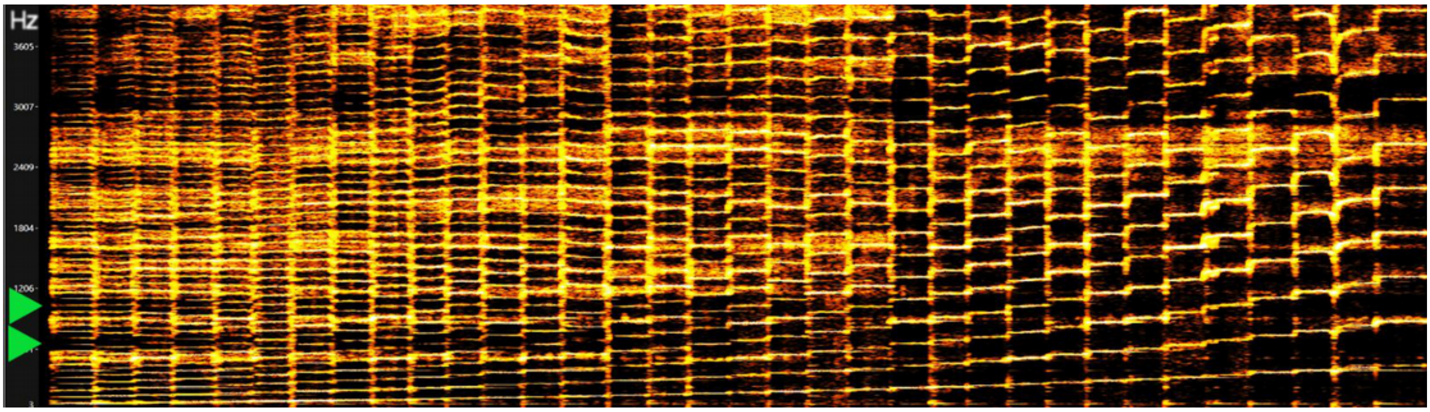
The sound recording of the scale with the microphone, shows relatively few differences between the Boxwood set-up, and the Padouk set-up, despite a perceptual classification from worst (Boxwood +) to best (Paduk ++++++).

The second, on the right, seems more regular in intensity of the harmonic "bars".

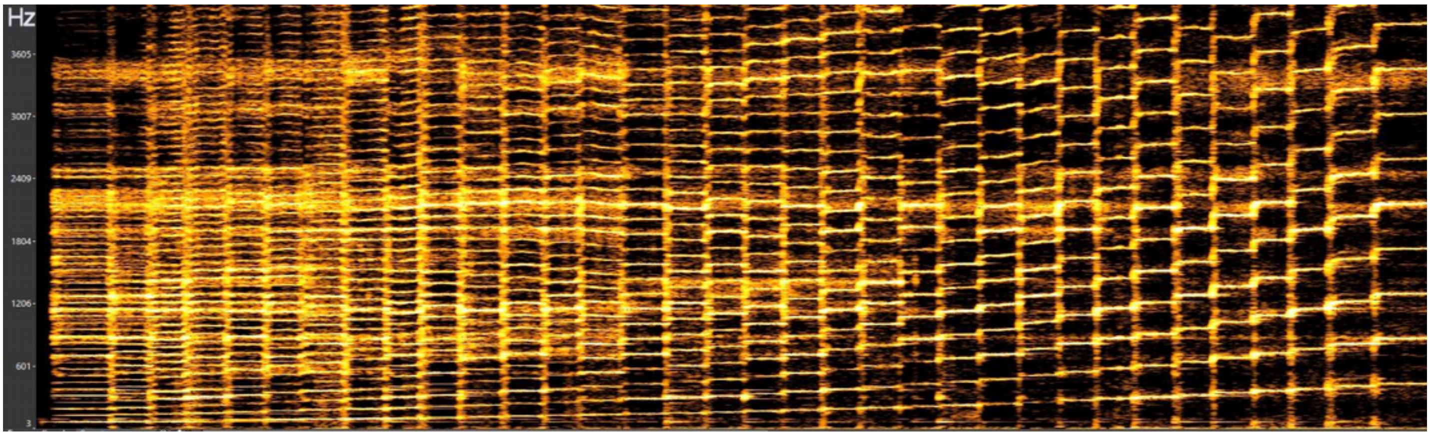
It doesn't look to be the same with the sound recording on the accelerometer, the vibrations which pass through the tailpiece, which appear to be less regular.

2. **Sonogram of the vibrations of tailpieces** accelerometer recording, of the same two tailpieces C300 and C71 :

- **Sonogram of the initial boxwood C300**, Rank +, from 0 to 4000Herz; 34 notes scale from C2 to A4



- **Sonogram of the Paduk C71**, Rank ++++++, from 0 to 4000Herz; 34 notes scale from C2 to A4



The display of the sonogram of the tailpiece highlights, on all or part of the instrument, frequency bands (horizontal)

- Darker: Where the amplitudes of the harmonics are reduced (The green arrows of the first C300 assembly: These two bands, depending on the tailpieces, from 600 to 900Hz, and from 1100 to 1300Hz seem to play a major role).
- Clearer: Where amplitudes are the strongest

On the whole, the Paduk set-up is, more homogeneous than the Boxwood in its harmonic emission.

The most liked tailpiece set-up have less alternation of dark and light bands: The harmonics have a more homogeneous amplitude distribution.

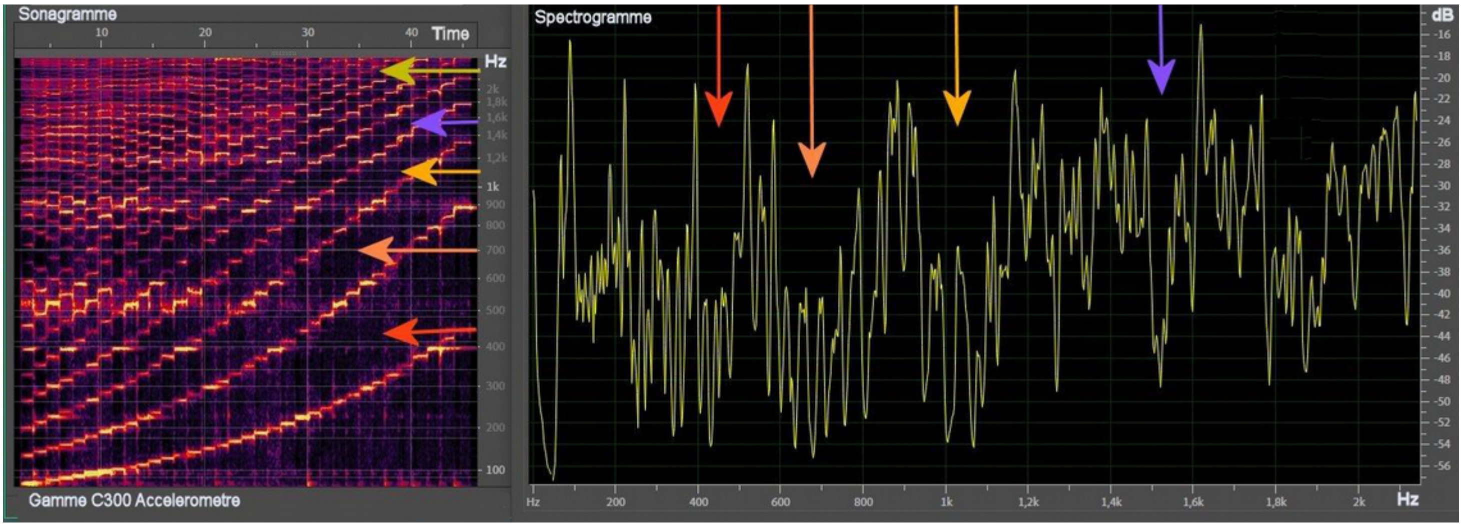
This method allows us to select quality criteria such as timbre and sound balance, but does not give information on power, precision of the attack or the note.

The spectrogram: **Shows the amplitude of the frequencies, for a given time selection, the scale.**

It is possible to refine this first study of timbre balance with the Sonogram, using the Spectrogram.

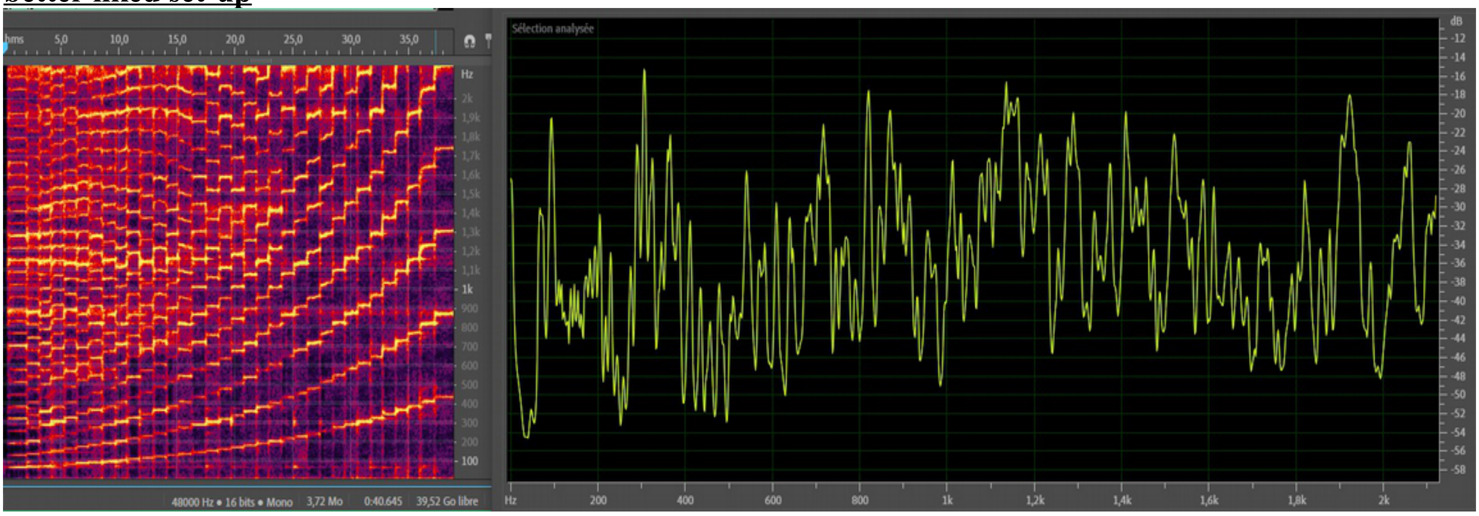
It will make it possible to specify, for a set-up, the frequencies concerned by a decrease or increase in the amplitude.

The dark horizontal bands of "mute" harmonic frequencies of the Sonogram, this time appear vertically, to the right of the spectrogram. Frequencies are measurable in Hertz on the sonogram, just like intensities in decibels on the Spectrogram.



Sonogram / Spectrogram of the C300 tailpiece assembly. Range 0 to 2kHz of the scale recorded with the accelerometer.

The same graph with the C71 tailpiece, shows much lower amplitude variations, on this perceptually better liked set-up



Sonogram / Spectrogram of the C71 tailpiece assembly. Range 0 to 2kHz of the scale recorded with the accelerometer

The spectrogram of the vibrations passing through the tailpiece, for each of the set-up, thus shows its weak or strong amplitude zones.

Do these ranges correspond to the resonant frequencies of the tailpieces?

Modal analysis **shows the frequency and amplitude of an object's specific resonance peaks.**

It also enable the calculation of the Modulus of Elasticity and the Damping coefficient, which are important sound descriptors.

The modal signature of a vibrating body is a real identity card of the sound.

Luthiers and acousticians have been studying the trends of historical instruments for years, hoping to find useful recipes for success for their own sake.

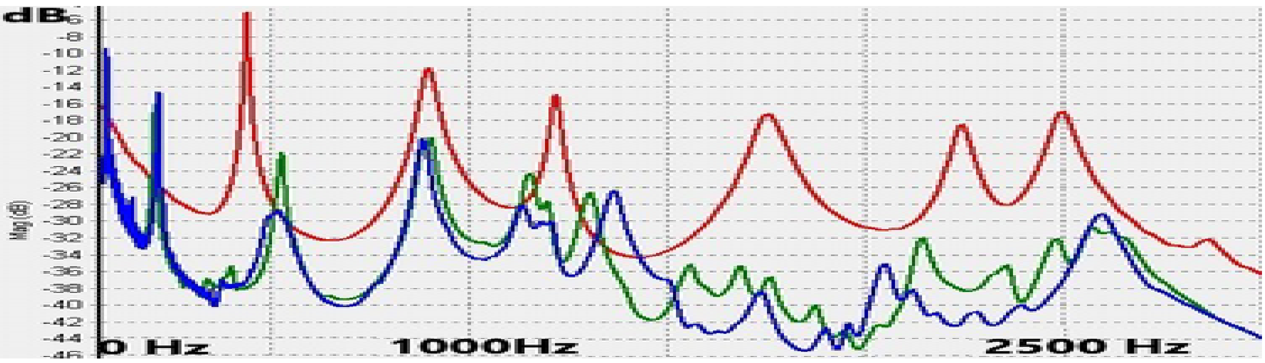
Unfortunately, these organological success factors are so complex that it is not enough to master and adjust the modes of a violin to make it successful.

The modal analysis for the interpretation of the vibration modes of instruments is still in its onset, when we want to understand their contribution to the final sonority.

The interest of this analysis on the tailpiece is clear, since it makes it possible to compare some set-up, on a musical perceptual level, accompanied by its acoustic measurements, by modifying only one factor, here, the species of the wood used.

Modal analysis of the tailpieces:

Each tailpiece had been studied in "free-free" mode (that is to say that each end is totally free) (Red curve), then under tightness on a "dead rig" (a mute set-up that simulates the angles and the tension of a real cello using strings and a tailgut)(green curve), and then on the cello (Blue curve). Indeed the tailpiece alone placed on a flexible net doesn't have the same vibratory behaviour when it's taut between the strings. This behaviour is modified again when set-up on a real cello.



Modal Analysis tailpiece C300 -Free-free- -on the "dead rig"- -on the Cello-.

We are not studying the first modes up to 200Hz which have already been analyzed in our previous studies. These are linked to the Rigid modes of the tailpiece, as well as to the A0 (vibration of the air inside the body) and B1+ (vibration mode of the body) modes of the cello.

We will not study the modes after 3000Hz either: Beyond this, the analysis is difficult, because it lacks repeatability, and the G.Stoppani software reaches its limit of significance, due to the overlap of the modes.

Global Analysis : Spectrogram and Resonance Modes

We were looking to find correspondences, between the frequencies of the resonance modes of the tailpiece, and those of the Sonograms / Spectrograms.

We find them on the Individual sheet of the C300 set-up below:

It is normal not to find an exact match for several reasons. **In particular** the overlaps of modes, and the differences between the types of set-up on a "Dead rig" (or on cello.

A correlation is found, (if not an exact frequency concordance) **between the weak or strong amplitude zones of the Sonogram** (first table), which one finds on the **Spectrogram**, (second table) as well as the frequencies of several m**odes of the tailpiece mounted on the "Dead rig"** (third table).

This partial match shows how the tailpiece is an acoustic filter, which promotes the transmission of its own modes, and thus contributes to the overall sound quality of the instrument.

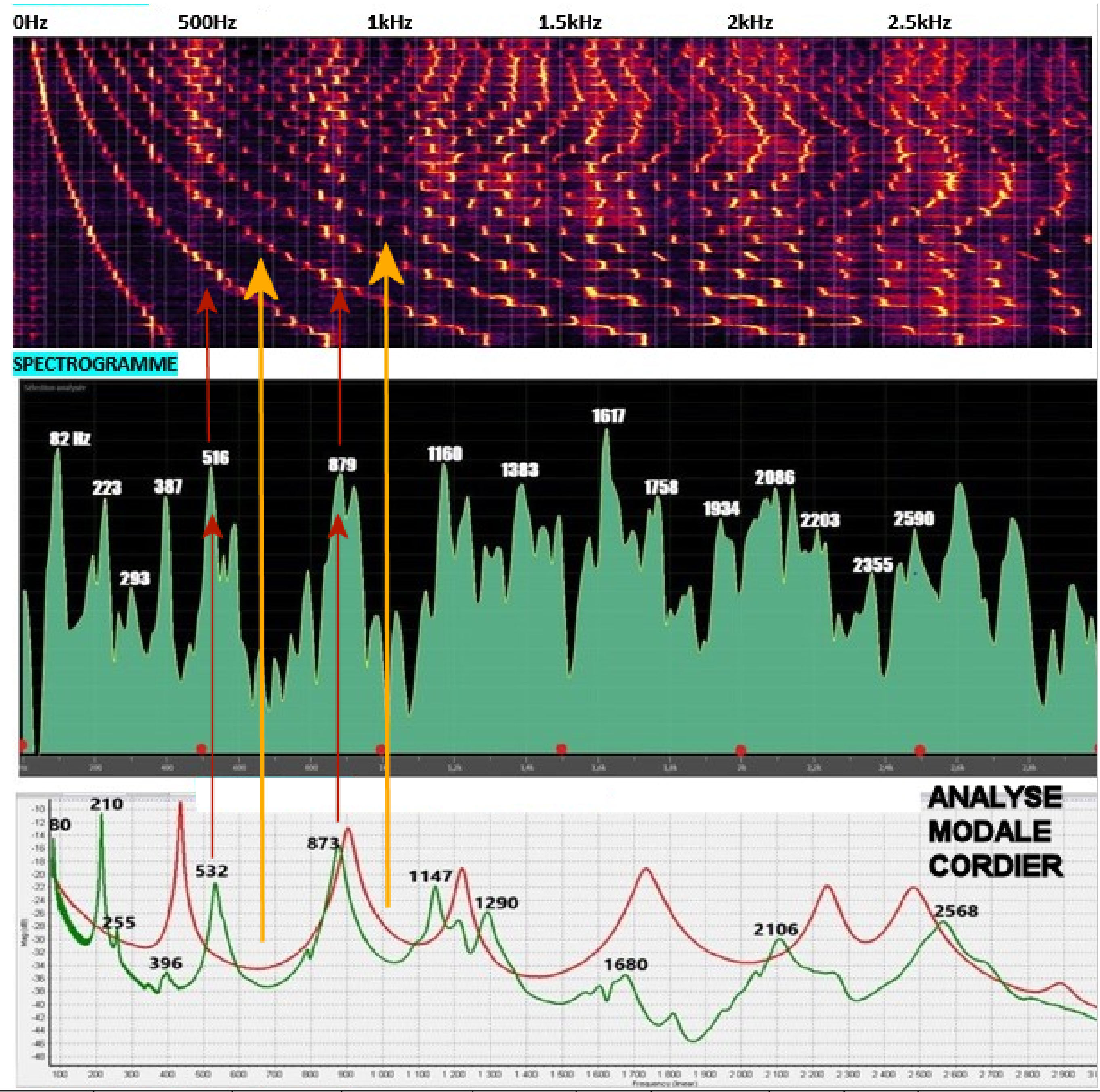
Individual Sheet of the **C300 Boxwood Initial** Perceptual test : +

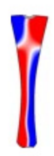
Tailpiece Free-Free

Density : 0.95 **Elasticity Modulus : 10.5 gPa** **facteur Q (Inverted Damping): 61**

Correspondence of spectrogram peaks with the green curve of tailpiece modes on the Dead rig

SONOGRAM (0 to 3 kHertz)



									**Modal Strains of the tailpiece**
Solid Body Mode "toggle"	**Bending 1**	**Twisting 1**	**Bending 2 Complex**	**Twisting 2 Complex**	**Complex**	**Twisting 2 Complex**	**Complex**	**Complex**	**Modal Strain Type**
NONE	**440Hz**	**899Hz**	**1223Hz**			**1759Hz**			**Free-Free** (unset tailpiece)
208Hz	**397 et 532**	**876**	**1145**	**1292**	**1670**		**2106**	**2563**	**On the "dead rig"**

Conclusions:

We have highlighted a contribution of the tailpiece to the overall tone of the instrument.

The vibration of the strings is transmitted to the body by the feet of the bridge, but is also transmitted by the vibrations of the tailpiece to the bottom nut.

A correlation appears between the sound quality of the instrument, and the vibrations of the tailpiece.

The vibration peaks of the Spectrogram also correspond to several Resonance Modes specific to the tailpiece, evaluated by a Modal Analysis on a Dead rig.

When the peaks of Resonance Modes are tighter in frequency, the spectrogram is smoother, and the sound quality of the instrument is better appreciated.

The density, the modulus of elasticity, and the damping coefficient of the wood used seem to be interesting markers, and require further experimentation.

Our Goals :

- Complete this analysis with other set-up.

- Better understand the spectrogram peaks that do not correspond to the modal peaks of tailpieces. These can be peak modes of the cello itself, or other accessories, such as the bridge or fingerboard.

- Understand the interaction of wood markers, by trying other species.

- Some of the interesting essences contain Extractables (Paduk, African Blackwood, Pernambuco, Rosewoods). Tests would be possible with leaching or, on the contrary, the injection of extractables into the wood, to study the modifications.

- Try to understand why "soft" tailpieces, like the Akustikus, very short cut tailpieces, can work well, why certain carbon reinforcements on tailpieces have favorable effects.

- Try to understand and complete our study on the evolution of tailpiece design at Stradivari.

- Complete this materials study with a "set-up" study (the tailgut length), which we had not yet completed.

About Wood Qualitative Markers:

	Boxwood Initial C300	***Paduk C70***	***Paduk C71***	***Densified spruce C66***	***African Blackwood C40***	***Pernambuco C25***
Perception test rank	+	++++++	++++++	++	+++++	++++
Density	***0.95***	***0.99***	***0.9***	***1.37***	***1.31***	***1.04***
Elasticity gPa	***10.5***	***19***	***18.6***	***28***	***17***	***26***
Damping (Q factor)	***61***	***134***	***105***	***72***	***102***	***132***

This index of markers requires confirmations with more measurements.

The density of the wood is not a critical factor if it is in the range of 0.9 and 1.4. A too light timber is rarely a good contributor. Very heavy woods are not a handicap.

A good modulus of elasticity is necessary, greater than 18 gPa. It is possible that a very strong Modulus (> 25) makes the attack of the note difficult.

A good quality factor (Q) (low damping wood), greater than 90, seems necessary to make a good tailpiece.