STRING "AFTER-LENGTH" AND THE CELLO TAILPIECE: ACOUSTICS AND PERCEPTION

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ABSTRACT

In a long term research on cello tailpieces, we have first identified the vibrating modes of a cello tailpiece mounted on a Dead Rig [1], and have worked on the possible influence of the wood on these modes. Among musicians and violin makers, several empirical theories exist about an ideal "after-length", i.e. the distance of the tailpiece to the bridge which leaves a small length of vibrating string. Here we describe on the parameters involved when varying the "after-length", and explore the influence of the position of the tailpiece on the modes and on the sound.

1. INTRODUCTION

On a modern cello, the tailpiece is where the four strings are attached. The tailpiece (C, fig 1) has one attachment at each end, and the setting is more or less standardized in its 3 lengths.: We call the "after-length" the distance B between the bridge (a) and the tailpiece (C fig.1). On the other side, it is held by the tail-cord (D fig.1) which passes around a saddle (d), and fixed by a loop around the cello endpin.

Empirical theories declare that the after-length should be 1/6th of the playing length of the string.

Our question is whether varying the three lengths B, C and D changes the motion of the tailpiece and the sound of the instrument. We attempt to make connections between acoustic measurements and the perception of sound by sound perception experts when varying the position and length of the cello tailpiece.

The three components B, C and D are interdependent in the "tailpiece chain" BCD. In order to isolate the *after-length* question, we used an adjustable tailpiece to characterize the influence of this *after-length* compared with the influence of the tail cord and of the tailpiece's length on the tailpieces modes on a Dead Rig and then on the vibration modes of a cello.

2. MATERIAL AND METHODS

2.1 Material

Two modern standard tailpieces in ebony and one adjustable tailpiece in African blackwood were used:

-Tailpiece T.1: ebony *(Diospyros)*, 62 g, length 235 mm.
-Tailpiece T.2: ebony *(Diospyros)*, 62 g, length 250 mm.
-Tailpiece T.3: African blackwood *(Dalbergia)*, 76 g, 235 mm, with double system of attachment both baroque and modern, two possible *after-cords:* one of standard length, the other with an extension of 23 mm ("baroque type" attachment) (Figure 2).

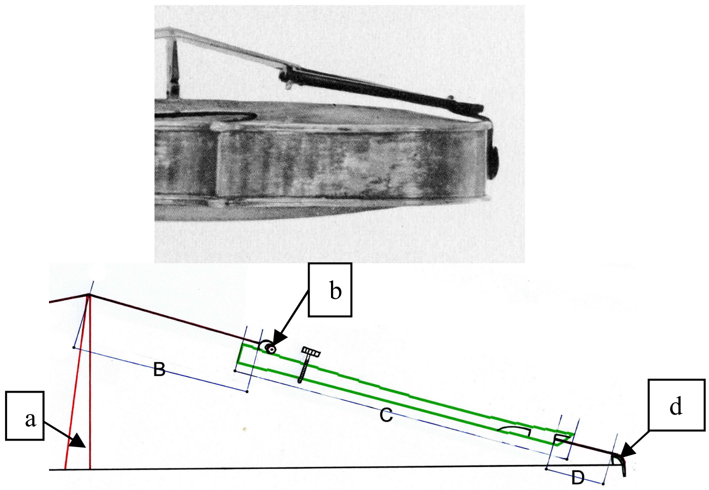

Figure 1. Profile of (from left to right) a: bridge, B: after-length, C tailpiece length with its stopping nut b, D:tail-cord length, saddle d. (Above, profile of the Stradivari violin "l'Aiglon".

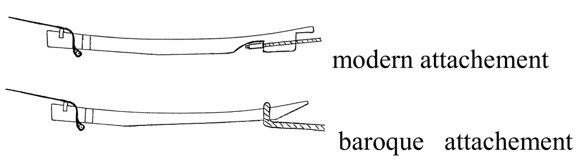

Figure 2. Tailpiece T.3, of length 235 mm, with two possible attachments. The attachments are made in composite fibers and do not stretch significantly whith 60 kg tension of the cello strings.

The Dead Rig is made of a strong metallic beam with no resonance at the modal frequencies we are studying, see [1]. It holds a string length and a fixed bridge at the same angle as on the cello, and an end attachment with the same dimensions as on the cello.

The violoncello is a good student cello made in Mirecourt in 1930.

As described in our papers on the modal analysis of the cello tailpiece [1], we used a 2g PCB impact hammer, a PCB uniaxial Accelerometer and George Stoppani's Software. George Stoppani's modal analysis software, gives the FRF to the hammering of specific points on the tailpiece, amplitude, damping, and an animated visualization of the mode shapes of the tailpiece and / or the cello.

2.2 Methods

On both the Dead Rig and on the cello, we have stretched and tuned cello strings with different *after-length* configurations of tailpieces. Three different methods were used: modal analysis of the tailpieces under tension, Bridge Admittance measurements on the cello, and sound perception of the cello played three expert listeners: the player and two violin makers.

The bridge admittance of the cello was measured by hammering at the treble side of the bridge, the response of the body was measured with the accelerometer at the top bass side of the bridge: it gives an RMS where the A0 air mode and the B1- and B1+ torsion modes of the cello are identified with their frequencies and modes shapes.

Repeatability is achieved in the modal analysis of the tailpieces on the Dead Rig with a mean of 300 measurements taken, and in the 10 admittance measurements of the cello's bridge for each tailpiece Set-up.

Perception learning by musicians leads to an expert type of listening different from that of non musician [2]. From the point of view of neurosciences, there is a change in cortex that is linked to learning experiences in both visual arts and music [3] and the training of the ear leads to a change in hearing perception and cognition [4] Thus, we argue that musicians but also some instrument makers have developed an expert type of perception, and this leads us to chose relevant experts: a professional cellist and two violin makers.

A chromatic scale, extracts of Bach's suite n°1 in G Major and of Brahms Sonata N°1 in E minor was played. Each expert listener expressed their perception of the instrument's power, balance, tonal quality, and dynamic range, precision of attack and wolf note. The latest is generally found on most cellos between E and G, on one or more strings.

Quantitative appreciation of the qualitative judgments, the semantic diversity of the terms employed by the musician and makers, and the influence of the room used for the test have their importance, and our protocol was chosen similar to one used by a violin maker in his workshop: The musician made her comments first in order to avoid the influence of the listeners. The maker who was not involved in the experiment spoke second. The third expert took notes of the comments and asked for explanation to get a more precise idea of what the expert meant to say, each expert being free in which order he reacted about the different parameters, because constraint would have spoiled their first immediate perception. Effectively, perception work has to take into account short and long term sound memory and comparisons two by two with short term perception memory of the experts was privileged.

3. RESULTS

3.1 Modal Analysis of the Tailpieces on the Dead Rig :

We compare seven different settings (Figure 3) on the Dead Rig giving four different *after-lengths*: 95, 115, 116, 128 mm (A standard *after-length* used today for cellos is 115 - 117 mm.)

For this, we use

- 3 different tailpiece lengths : tailpiece T.1: 62 g, length 235 mm. tailpiece T.2: Ebony, 62 g, length 250 mm, *after-length* 116 mm. tailpiece T.3 with two possible *after-lengths*.
- Six different tail-cord lengths : 51 mm, 39 mm, 30 mm, 28 mm, 18 mm, 10 mm.

These Set-ups are summarized in Figure 3.

Type of setting	After-length	Tailpiece	Tail cord
Set-up 1	116 mm Standard	235mm T.1 Standard	30mm Standard
Set-up 2	95 mm Short	250mm T.2 Long	30mm Standard
Set-up 3	116mm Standard	235mm Standard T.3 **adjustable**	51 mm **Long**
Set-up 4	128mm Long	235mm Standard T.3 **adjustable**	39mm **Long**
Set-up 5	128mm Long	235mm Standard T.3 **adjustable**	18 mm Short
Set-up 6	116 mm Standard	235mm Standard T.3 **adjustable**	28mm Standard
Set-up 7	115mm Standard	250mm T.2 Long	10mm Very short

Figure 3. Types of settings for the experiments: colors are used for reading the following curves.

3.1.1 Comparison of Standard and Short After-length

T.1 (standard) and T.2 (long) are compared with two different *after-lengths*: normal (116 mm: Set-up 1) or short (95 mm: Set-up 2) and the same standard tail-cord length.

The first modes of the tailpiece on the Dead Rig, in group I and group II (Figure 4) as we have shown in previous articles [1] are rigid Body Modes. On the Dead Rig, we get the same frequencies for a normal Set-up and for a smaller *after-length*.

In group III (the bending and torsion modes), the RMS shows strong differences between #6 (Bending 1) and #7 (Torsion 1): the longer tailpiece has a lower frequency for the flexion and torsion modes (beam modes) indicating a greater flexibility of the tailpiece itself giving them more amplitude. The shorter tailpiece and longer *after-length* have lower energy in amplitude.

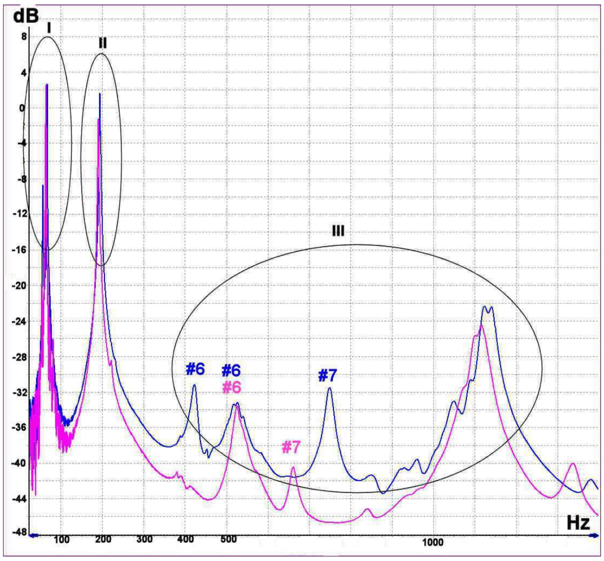

Figure 4. Test 1 : Modal analysis of the tailpieces T1 and T2 on Dead Rig, RMS of Set-up 1 (pink) and Set-up 2 (blue).

Here, we see that the modal differences are due to the length of the tailpiece, which is less flexible in the shorter tailpiece (Set-up 1) in the bending and torsion modes, rather than effects coming from the *after-length* modification.

3.1.2 Comparison of three different tail cord lengths

We compare the Set-up 3, 4 and 5 on the same Adjustable Tailpiece T.3monted on the Dead Rig (Figure 5).

- Set-up 3: standard *after-length*, long tail cord.
- Set-up 4: long *after-length*, standard tail cord.
- Set-up 5: long *after-length*, short tail cord.

3.1.2.1 Effects on Swing and Rotating Modes (Group I):

For modes #1, #2, #3 (the swing and rotating mode (see [1]) around 57 Hz) we have shown previously that the tailpiece has rigid body modes and that it swings and rotates on its attachments. The three Set-up show the same frequencies. Amplitudes of Set-up 3 with standard *after-length* and a long tail cord is significantly above the two others (8.2 dB, 9 dB).

3.1.2.2 Effects on See-saw Modes (Group II):

For modes #4, #5, we found previously that the tailpiece on the Dead Rig present see-saw balancing modes around 200 Hz: Here, frequency rises +10% between Set-up 3 and Set-up 4 with a diminution of 23% of the tail cord length. Frequency rises + 25 % for a diminution of 54% of tail cord. The increase in frequency is significant with the diminution of the tail cord.

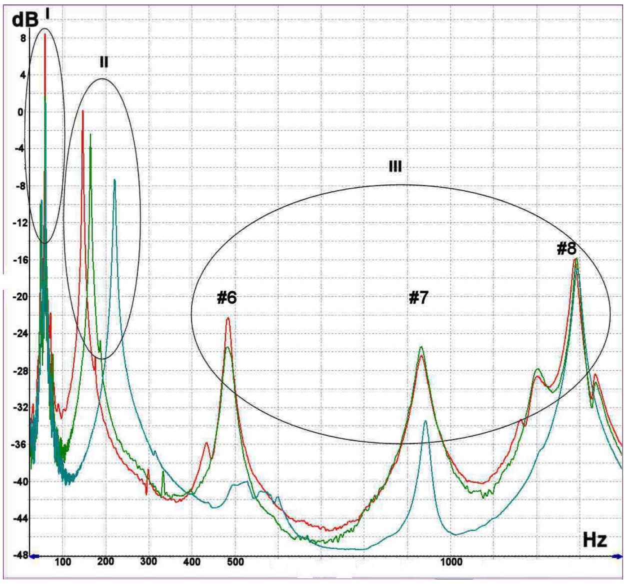

Figure 5. Modal analysis of tailpiece T.3 on Dead- Rig: Long tail cord: Set-up 3 (red), standard tail cord: Set-up 4 (green), short tail cord: Set-up 5 (turquoise).

3.1.2.3 Effects on Bending and Torsion Modes (Group III):

Modes #6, #7, #8, of the tailpiece on the Dead Rig were found to be bending and torsion modes just above 450 Hz: Here, frequencies are very similar for Set-ups 3, 4 and 5 of the adjustable tailpiece.

Amplitudes are similar for Set-up 3 and Set-up 4, while the amplitude of Set-up 5 is lower in the middle range: the tail cord being very short damps the #7 bending and torsion mode.

Thus, it is more the length of the tail cord that affects these modes, and not so much the *after-length*. When the tail cord is shorter, in Set-up 5, the movement is damped in amplitude but the flexibility of the tailpiece itself is not much affected.

3.2 Modal analyses of the tailpieces on cello

Bridge Admittances give us the principal Body Modes of the cello mounted with different Set-up. We compare the effects of two different *after-lengths* and then of three different after cord lengths on the cello to compare them later with the tailpiece modal analysis on the Dead Rig results.

3.2.1 Comparison of standard and short after-lengths

T.1 (standard) and T.2 (long) are compared with two different *after-lengths*: normal (116 mm) or short (95 mm,) a shortening of 21 mm (-15, 8%) between the two; the same standard tail-cord length is used. We explore the coupling of the tailpiece with the cello Body Modes extracted from Bridge Admittance measurements (Figure 6).

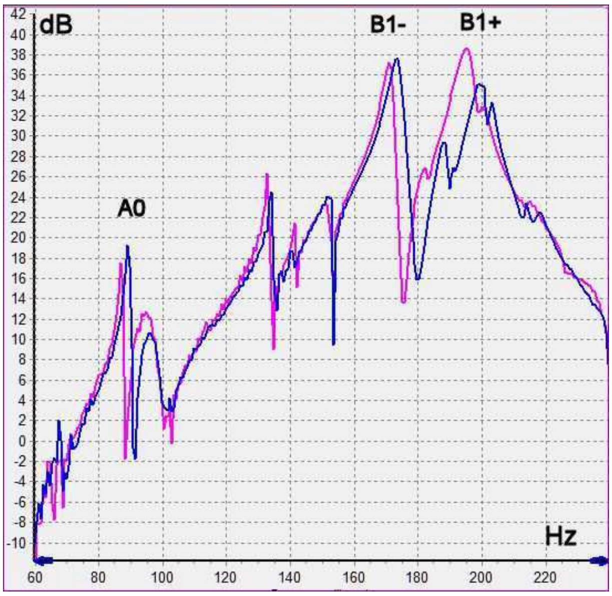

Figure 6. Cello Body Modes for standard Set-up 1 (pink) and Set-up 2 (blue) with long tailpiece T2 and shorter after length. Same tail cord length for both**.**

The difference between the standard Set-up and the shorter *after-length* is very slight:

Near A0, two peaks are visible: the lower in frequency is connected with the first modes of the tailpiece (group I figure 4); the second corresponds to the first air mode of this cello A0 which is around … There is a deep split which corresponds to the coupling of the tailpiece and the cello, and it is similar in both Set-ups. However, when shortening the *after-length* from Set-up 1 to Set-up 2, i.e. from 116 mm to 95 mm (-15, 8%), the first cello air mode A0 rounded peak on the right is raised only 2% in frequency and decreases (-2 dB) in amplitude, while the tailpiece peak on the left is also raised about the same amount with a slightly higher amplitude.

Body Cello Mode B1- shows even less difference between the two Set-ups: an increase of 1, 9 % in frequency, and similar amplitudes.

Body Cello Mode B1+, as the *after-length* is shortened goes up 2, 5% in frequency and is more separated in three different peaks. The standard Set-up has higher amplitude on B1+. This is the most affected cello Body Mode.

3.2.2 Comparison of three lengths of tail cord

The tail cord lengths seem to be of relatively greater importance as we have seen in preceding comparisons (see 3.1.2). We compared the following set ups on the cello (figure 7):

- Set-up 4 is the adjustable tailpiece with long tail cord and long *after-length*.
- Set-up 5 is the adjustable tailpiece with shorter tail cord and long *after-length*.
- Set-up 2 is a longer tailpiece with standard tail cord and short *after-length*.

We can see that the cavity mode A0, and the two main Body Modes B1- and B1+ of the cello change with the different settings of the tailpieces. The two normal length tailpieces (Set-up 2 green and 5 turquoise) do not react in the same way, which show the importance of their attachments.

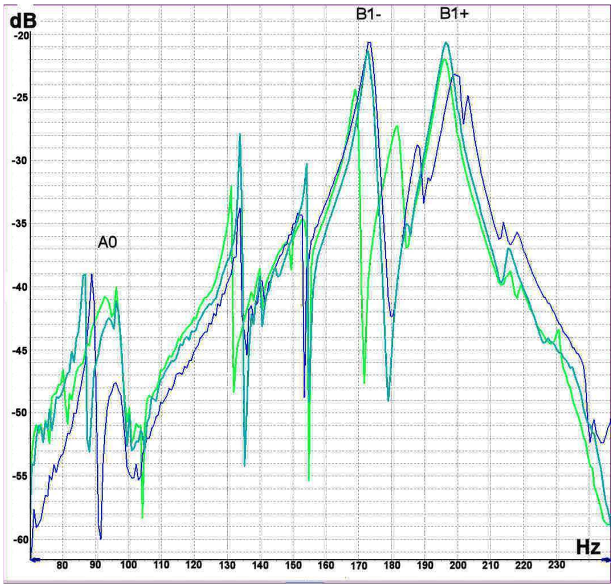

Figure 7. Cello Body Modes for long tail cord: Set-up 4 (green), standard tail cord: Set-up 5 (turquoise), and short tail cord: Set-up 2 (blue) with long tailpiece T2 and shorter after length.

*3.2.2.1 Effects of tail cord length on the Air Mode **A0:** (92-95 Hz)*

With Set-up 2, the frequency of mode #3 of the tailpiece itself (around 75 Hz), is distinct from cello A0 frequency (around 92 Hz). The amplitude of A0 lowers very little (-2 dB) when the tail gut is shortened, from Set-up 4 to Set-up, 5. But from a long to a short tail cord, the cello Body Mode A0 peak splits in two, indicating a coupling interaction of the tailpiece mode #3 with the cello mode A0 when shortening the tail cord. The split of A0 is even more striking, and the amplitudes diminish even more (- 8 dB) when the *after-length* and the tailcord both get smaller with a longer tailpiece in Set-up 2.

3.2.2.2 *Effects of tail cord length on the cello Body Mode B1-: (169–173 Hz)*

The B1- peak is split for Set-up 4 (*after-length* and tail cord longer), a new peak appears at 181 Hz between B1- and B1+ showing a strong effect of the coupling. There, the amplitude is minimum (- 4 dB). Set-up 2 and 5 (*after-length* and tail cord smaller) have a very clear and strong B1- peak.

*3.2.2.3 Effects of tail cord length on thecello Body Mode **B1+:** (195-199 Hz)*

B1+ peak is high and clear for Set-up 5 (Turquoise) and Set-up 4 (green) although a little lower in amplitude for the latter.

Mode B1+, with Set-up 2 (blue), is loosing a little amplitude, leaving a main peak with less amplitude and one smaller peak on each side. This indicates the coupling of one or two modes of the tailpiece and a consequence of the split of A0 on A1 (which on cello, is just below B1+). In this Set-up, the tail cord is very small, attaching more firmly the bottom of the tail to the body of the instrument.

It seems that while adjusting the Set-up of the tailpiece, the main modes of the cello can be coupled with modes of the tailpiece. This is shown by the split of the peaks into different peaks which lowers the amplitude of the main Body Mode. Set-up 4 with long *after-length* and long tail cord splits dramatically A0 and B1-. Set-up 5 where the tail cord is very small, attaching more firmly the bottom of the tail to the body of the instrument splits B1+ in three.

3.3 Perception results

The cello used for this test is usually qualified as powerful, open, and slightly more powerful and hollow towards the treble, with a clear sound (in a sense of a lack of roundness). It has a strong wolf note on the F# on the G string.

3.3.1 Tailpiece T.3- adjustable tail cord length:
When lengthening the *after-length* from Set-up 6 to Set-up 5, not much change is noticed. The sound gets a little more precise, the tone nicer, with a little unbalanced treble and a more metallic sound; less dynamic for 3, from small to extra long, the balance between bass and treble is better, treble notes are better and have a larger dynamic range. The whole sounds better, with the basses more open and global resonance also, the precision of attack remaining. However, the wolf note is now strong. The wolf note was reduced with a medium tail cord length.

3.3.2 Tailpiece T.2- Short to Standard After-length:
When lengthening the *after-length* while diminishing the tail cord, from Set-up 2 to Set-up 7, the main sound gets better, from a powerful and metallic character with attack difficulties and unbalanced trebles, towards much better basses and trebles, easy playing and a lesser wolf note.
The instrument is more difficult to play but globally has a better tone.

4 SYNTHESIS

With three different approaches: modal analysis of tailpieces under tension on a Dead Rig, comparison of the main Body Modes of the cello obtained from the Bridge Admittance measurements, and musical perception of the instrument, we have tried to isolate the effects of the variability of the *after-length*. Even though this dimension is linked to that of the tailpiece and of the tail cord, we have isolated this parameter by using artifacts, such as an alternate use of baroque type or modern type of attachment on same adjustable tailpiece, and the use of tailpieces of different lengths. The analysis is then approximate, and is getting more precise with other complementary tests which are not mentioned in this study, but are included in a PhD in progress. The perceptive analyses remain modest and only qualitative in order to confront dynamic mechanical measurements with perception for each Set-up

4.1 Swing and Rotating Modes (Group I) and A0:

Group I is the group of the three first modes of the tailpiece described by Stough [5] and by Fouilhé and al. [1]. They have a strong amplitude around the frequency of the lowest string of the cello (C = 65,4 Hz) and are linked together, however, they do not produce any perceived sound because A0 acts as a filter of lower frequencies.

When both the *after-length* and the tail cord get smaller with a longer tailpiece in Set-up 2, the peak of B1+ is split, which indicate a coupling of some kind.

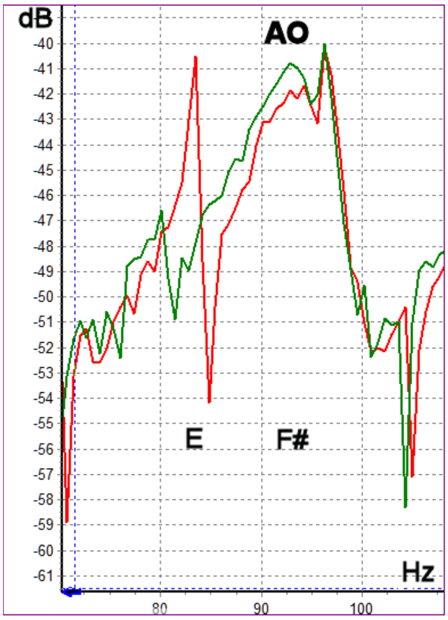

Figure 8: Cello Body Mode A0 (from the Bridge Admittance) for Set-up 3 (red) and Set-up 4 (green).

The large red peak of Set-up 3 seen at 82 Hz on the left of the cello's A0 (93 Hz) (Figure 8) correspond to Tailpiece mode #3 at 75 Hz on the Dead Rig. This can be proved when damping with the hand the vibrations of the head of the tailpiece, then the peak at 83 Hz disappears, leaving a single A0 peak.

A0 and #3 could be coupled in some Set-up, for instance in Set-up 3 but not in Set-up 4.

However, when the *after-length* or tail cord are varied Group I is not affected in frequency but only slightly in amplitude.

As early as 1819, Felix Savart who was working with Vuillaume mentioned the importance of the tuning of A0 with other modes [7]. Carleen Hutchins [8] and Jim Woodhouse [9] confirmed the importance of the tuning of this mode. Recently, Bissinger has shown a correlation between the amplitude of A0 and the tone quality of violins [10].

Thus we have shown that the coupling of the tailpiece with A0 divides the peak of the resonance of the instrument, thus sharing the energy between A0 and that mode. This lessens the sound quality especially in the bass register. It is thus preferable to un-tune the tailpiece from the A0 by means of setting up *after-length* and tail cord.

4.2 Coupling of the Tailpiece's See-saw Modes (Group II) and the Cello's Main Body Modes B1- and B1+

Two rigid Body Modes, #4 and #5, belong to group II and have been described by Stough [5] and Fouilhé [1] (Mode #4=Rh), they are see-saw modes. Their frequency is near B1- and B1+ below 200 Hz, in a range where a coupling interaction will influence the tone.

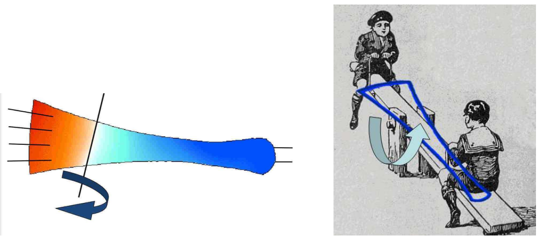

Figure 9: Mode #4 of the tailpiece under tension : strong see-saw motion, see [1].

Because of the asymmetric lever which is shorter towards the head of the tailpiece (in red Figure 9), because the tailcord firmly holds it on the lower end (in blue), Mode #4 is little affected by the *after-length* but more by the length of the tail cord.

In Set-up 3, 4 and 2, the tail cord gets progressively smaller at each Set-up; the end of the tailpiece is maintained progressively stiffer near the saddle. The consequence is an increase in frequency and lowering amplitude of Mode #4 (figure 5). The perception is that the cello's sound is powerful, richer in harmonics, but more demanding in the emission.

In Set-up 4, when the tail cord is at maximum length, if Mode #4 gets below the frequency of B1-, B1+ splits in two peaks (Figure 7). The sound of the instrument is modified, and there is a diminution or even disappearance of the wolf note. The sound is milder, less powerful, less aggressive, lower harmonics are lost, the general tone has less character, and the articulation is less precise under the bow.

The tail cord can thus be adjusted between this two extremes but one can expect that it is dependant also on the weight of the tailpiece.

5 CONCLUSIONS

The importance of the lengths of the "chain" = *after-length* + tailpiece length + after cord has been described with modal analysis and related to tonal adjustment.

Variations in *after-length* from standard to smaller *after-length* do not significantly affect the tailpiece modes frequencies measured on the Dead Rig, nor the Body Modes of the cello on which the Set-ups were tried, except on the B1+ whose frequency was raised 2,5% with a -15, 8% *after-length*. The *after-length* has been found to be more sensitive to diminution than to increase around the standard length.

The changes in the standard tailpiece lengths (of 116 mm ± 5 mm) did not affect sensibly the frequencies of the Cello Body Modes nor the perception of the tone, except where the flexibility of the tailpiece itself is involved.

It is more in the variations of the tail cord that differences were measured. Frequency rises of + 25 % for a diminution of 54% of tail cord have bee noted. The increase in frequency is significant with the diminution of the tail cord, and these changes were related to perception changes.

It is known that the air mode of the cello A0 is important for the quality of lower tones: The higher in frequency and the steeper is the A0 peak, the quicker there is saturation when pushing the string hard with the bow. On the opposite, when the A0 peak is moved and widened towards lower frequencies, the general tone of the instrument is lower, and the bow can be pressed harder.

Here, we have found how tailpiece adjustments can be used to move A0 in order to enhance these effects when desirable, as well as how it acts on the wolf note.

Other factors are to be associated like weight and wood variations, and have as much importance in the tonal adjustments of the cello.

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