

# Experimental Modal Analysis of Violins Made from Composites <sup>†</sup>

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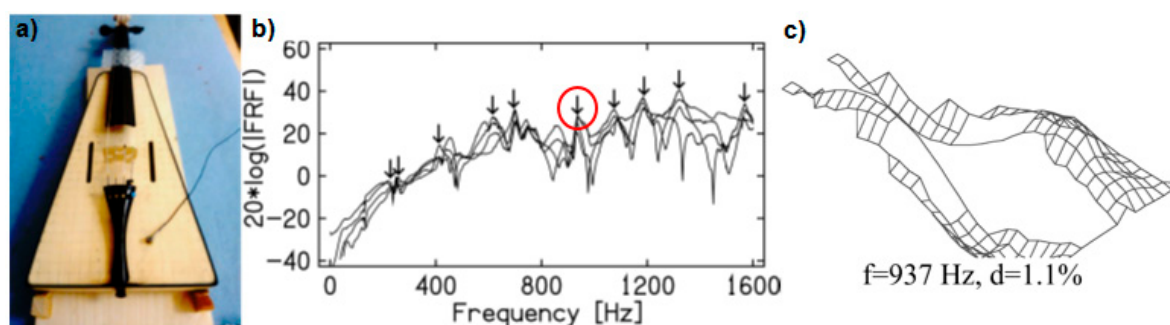
**Abstract:** Six prototype violins made from composite materials are made and investigated using experimental modal analysis with the roving hammer method. The average FRF's obtained show an influence of the materials on the vibrational response up to 2200 Hz. The A0 breathing mode and B1- mode are identified and are found to be significantly lower than in classical wooden violins. Additional measurements with a Laser Doppler Vibrometer and shaker found the same modes with a small difference in frequency (3–8 Hz).

**Keywords:** violin; modal analysis; composite

## 1. Introduction

The vibrational modes of wooden music instruments like the guitar and violin are well documented in literature, and provide insight in the dynamics of the instrument [1,2]. Although there is discussion about the link between the vibrational modes and the actual sound radiation [3], an experimental modal analysis can explain differences in the radiated sound parameters. For example, a different placement of the bassbar and lack of arching in a trapezoidal violin can result in more symmetric vibrational modes (Figure 1), which on their turn result in a lack of brilliance in the sound [4]. As such, experimental modal analysis is a valuable tool to examine the performance of experimental music instruments.

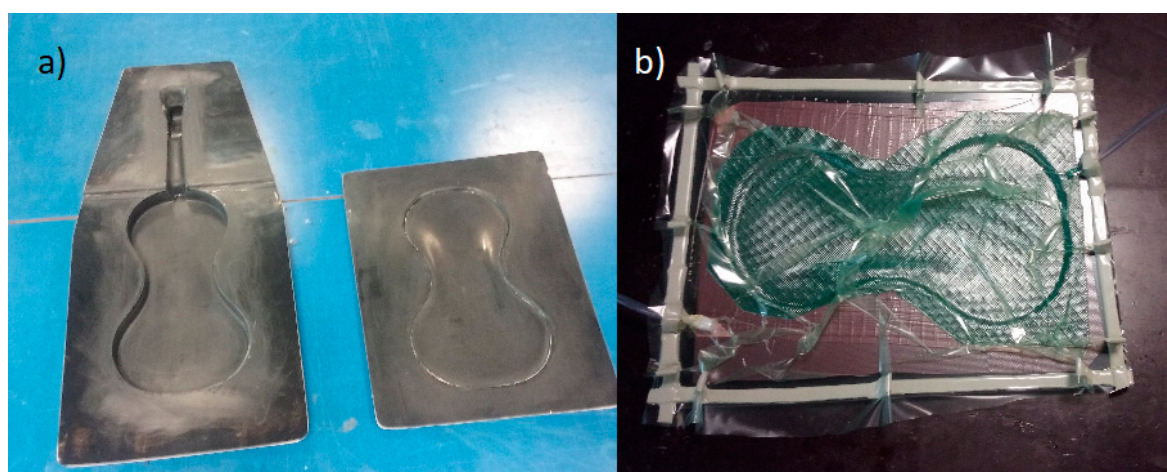
Recently, instruments made from fiber reinforced polymers (or composites) have successfully entered the market. Companies such as mezzo-forte Streichinstrumente, Luis and Clark and Elixir Violins are producing carbon fibre reinforced polymer (CFRP) violins, whilst BlackbirdGuitar makes guitars and ukuleles from both carbon and flax fiber reinforced polymers. Composite materials seem a compatible alternative to tonewood in sound production and especially durability, yet the research on composite music instruments is a very new field and mostly limited to the making and comparing of one prototype to a classic wooden instrument [5]. However, none of these publications compare instruments made from different composites and assess which changes in vibrational behavior are due to the effect of geometrical design and which are the effect of the used material.



**Figure 1.** (a) Trapezoidal violin with accelerometer, (b) FRF function of 4 points on the trapezoidal violin, (c) the vibration mode on 937 Hz.

## 2. The Prototype Violins

To objectively assess the influences of different composites on the vibrational behavior and sound of violins, six prototype violins were constructed in the laboratory. The model is based on that of a classic violin (Stradivari 1716), but adapted to make mold fabrication possible. The violins have the same geometry (apart from inevitable manufacturing variability). The ribs, back plate and neck of all the violins is made from woven carbon composite. The soundboards (or top plates) are made from different materials. All composite parts were made using vacuum assisted resin transfer method (VARTM). Figure 2 shows the moulds used for construction of the prototypes (a) and the top plate under vacuum before infusion.



**Figure 2.** (a) Mould for body (left) and top plate (right), (b) top plate production through VARTM.

The thickness of the soundboard of a classic violin is made so it is rigid enough to withstand the pressure of the strings without collapsing over time, as well as being flexible enough to vibrate easily [6]. For this purpose the required thickness of the soundboards for each material was calculated using laminate theory. In this way all top plates have a similar bending stiffness as classic violin along the axis.

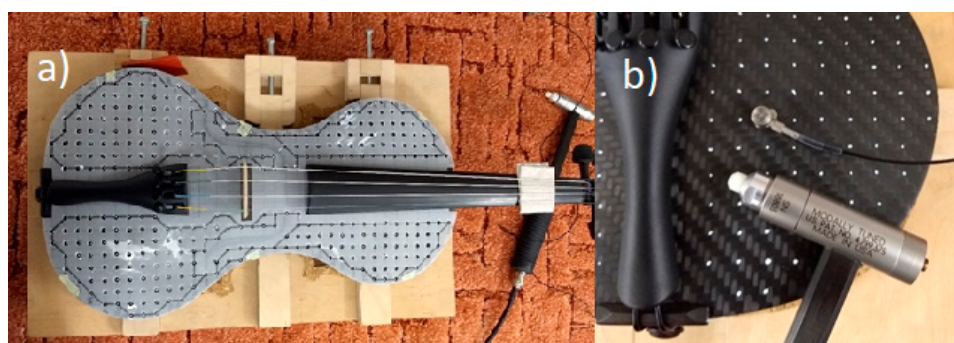
Figure 3 shows the six manufactured violins: 1. Woven carbon composite (hereafter named CTA), 2. Unidirectional carbon composite (CUD), 3. Classical tonewood (SPRUCE), 4. Unidirectional flax composite (FLAX), 5. Carbon-Nomex Sandwich (HC) and 6. again woven carbon composite (CTB). Instrument nr. 6 was included to assess the reproducibility of manufacturing and experiment results. In this way, we can study the effects of the material type on the vibrational performance of the soundboards.



**Figure 3.** Six prototype violins with soundboards made from different materials.

### 3. Modal Experiment

Experimental modal analysis describes the dynamics of any vibrating system in terms of modal parameters. For analyses of music instruments, the natural frequencies and damping, as well as deformation patterns (mode shapes) associated with them are thought to have a large effect on the sound produced [3,7]. Experimental modal analysis can be performed in many ways. For our first analysis of the composite violins we chose the method of a roving impact hammer and a fixed response measurement point, as this method has been found to work well for music instruments and is already well described in previous papers [8–10]. On each violin, 348 predetermined points were marked as shown in Figure 4a, the distance between the points on the grid is 10 mm.



**Figure 4.** (a) Grid on top of one of the violins for marking the points, (b) mounted accelerometer on point 84 and impact hammer.

The violins were fixed in a mold which clamped the instrument on its edges, as shown in Figure 4a. An ONOSOKKI NP-2910 accelerometer, with a mass of 2 g and sensitivity of 0.3 pC/m/s<sup>2</sup> was mounted with bee-wax on point nr. 84. The instrument was excited on all points by an impact hammer (PCB Impact Hammer 086C05; sensitivity 2.25 mV/N). With 4096 FFT lines and a measurement range of 0–3200 Hz a spectral resolution of 2 Hz was reached. The quality of the measurement was controlled by means of the coherence and five averages. If the coherence was not consistently close to 1 the measurement was repeated. From all FRF's measured, the SMS STAR-Modal R software package calculated possible modes. Based on the stability of the frequency and damping, as well as the estimated damping, stable modes were selected for further examination.

From each violin, the same 10 measurements points were used to calculate average FRF's from all violins, as displayed in Figure 5. To make it easier to differentiate amplitude differences between the different violins, averages were taken in 200 Hz bands.

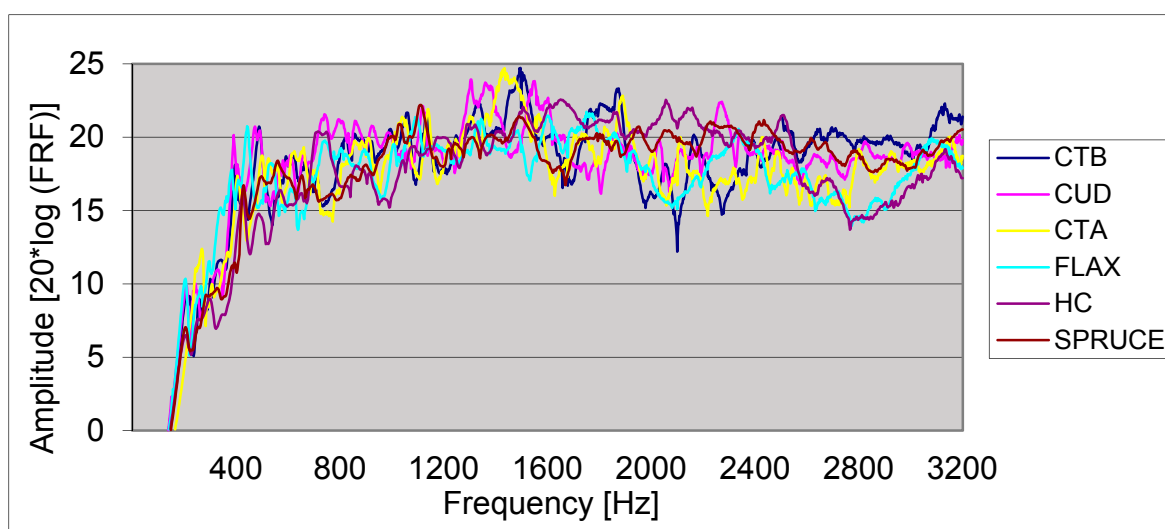


Figure 5. Average FRF of all prototype violins.

#### 4. Results and Discussion

As we can see in Figure 6, the average amplitudes in 200 Hz bands of CTA and CTB, which are made to be identical, show only small differences up to 2200 Hz. The top plates made from other materials, show larger amplitude differences. These results seem to indicate that material properties have a distinct and repeatable influence on the amplitude of violins up to 2200 Hz.

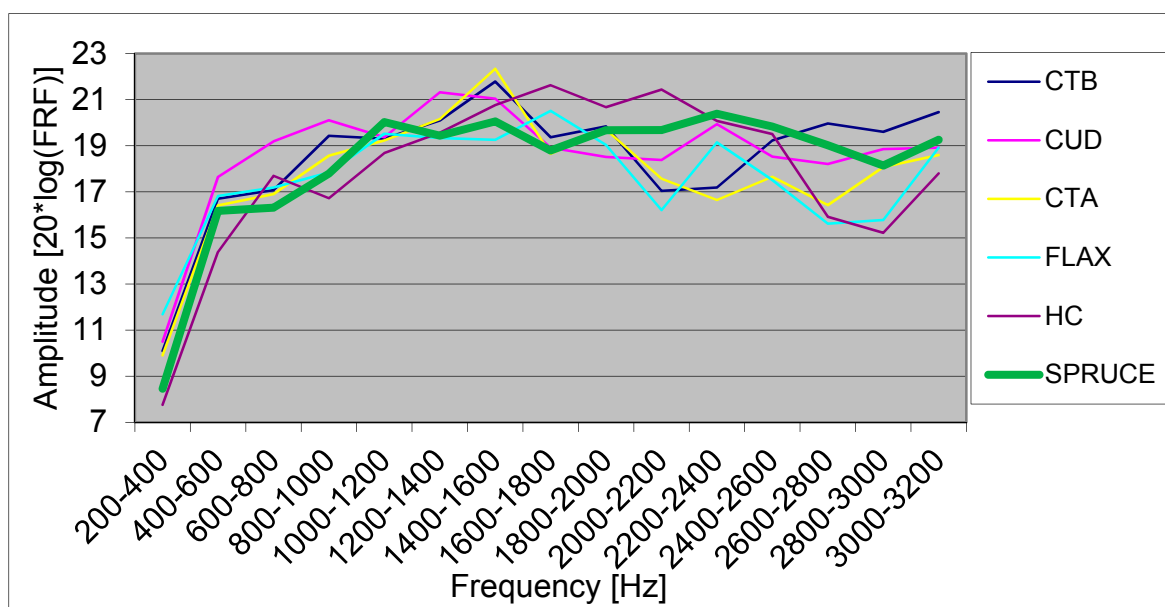


Figure 6. Average FRF of all prototype violins in 200 Hz bands.

Spruce, the material used normally for soundboards, has a rather low amplitude up to 1000 Hz, after which the average amplitude remains quite stable. HC starts off with the lowest amplitude up to 1400 Hz, with the only exception between 600–800 Hz. The material then shows a peak between 1600 and 2200 Hz, after which the amplitude drops again rapidly. Flax starts off with the highest average amplitude in 200–400 Hz. It then shows only small differences with spruce up to 2000 Hz. CTA and CTB both show a peak between 1400–1600 Hz, after which they both drop until they



separate around 2200 Hz. CUD shows a higher amplitude in the lower frequencies, especially between 600–1000 Hz, after which the differences with spruce become less distinct.

The mode shapes of a violin in the lower frequencies are well described in literature [3] and are by some believed to have a large influence on the produced sound of the instrument [7,10]. Two clear modes could be recognized, the A0 breathing mode and a B1 mode, most likely B1- (see the results in Table 1). A0 is marked by a movement of the entire plate around the bass bar. B1- has a strong motion in the lower bouts, separating it from the upper bouts by a nodal line. The frequency on which these modes are found is lower than usual for violins. A0 is normally found at  $275 \pm 9$  Hz and B1- at  $476 \pm 16$  Hz. As the spruce soundboard shows a similar drop in mode frequencies as the other materials, this is most likely caused by other differences between these prototypes and a classical violin like the design or material of the back plates, ribs or neck.

**Table 1.** A0 and B1(–) modes found in the prototype violins.

	CTB		CUD		CTA		Flax		HC		Spruce	
	Hz	%	Hz	%	Hz	%	Hz	%	Hz	%	Hz	%
A0	221		200		251		198		192		199	
B1-	393	2.10	391	2.64	409	2.43	380	3.38	423	2.36	424	2.57

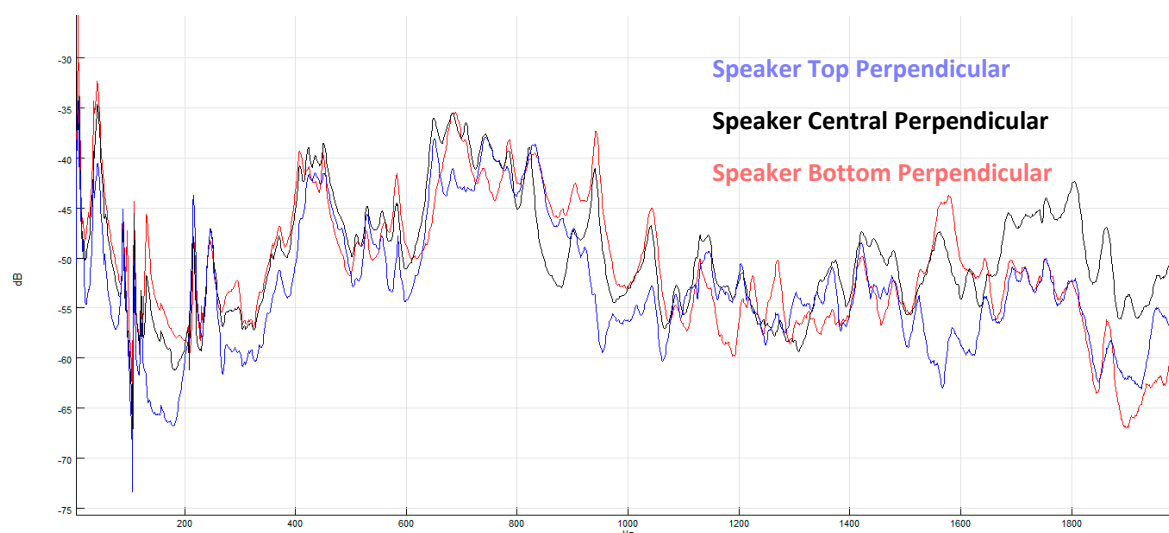
As the A0 mode is so low, no good estimations could be done on the damping of the specific mode. For B1- however, the only trend that we can see is the higher damping of flax. As CTA and CTB show a difference of 0.54%, this shows that other differences we might observe in the damping of B1- will most likely be caused by other properties than the material. Some research suggests that a lower B1 mode might contribute to a better sounding instrument in classic wooden violins [10]. If this is the case for violins made from different materials as well must be verified through listening tests, which are ongoing.

#### 4.1. Other Measurement Methods for Modal Analysis of Violins

Although the previous method has been often used to investigate music instruments, the influence of the accelerometer mounted on the lightweight plate cannot be excluded. Replacing the measurement device (accelerometer) by a Laser Doppler Vibrometer allows for a contactless measurement point. In this case a 3D Infrared Scanning Laser Doppler Vibrometer (Polytec PSV 500 3D HV Xtra) is used, both the in-plane and the out-of-plane vibrational response can be studied. An additional benefit of a scanning laser is that the excitation place can be fixed, which can allow for both easier and more repeatable measurements.

##### 4.1.1. Excitation through Speaker

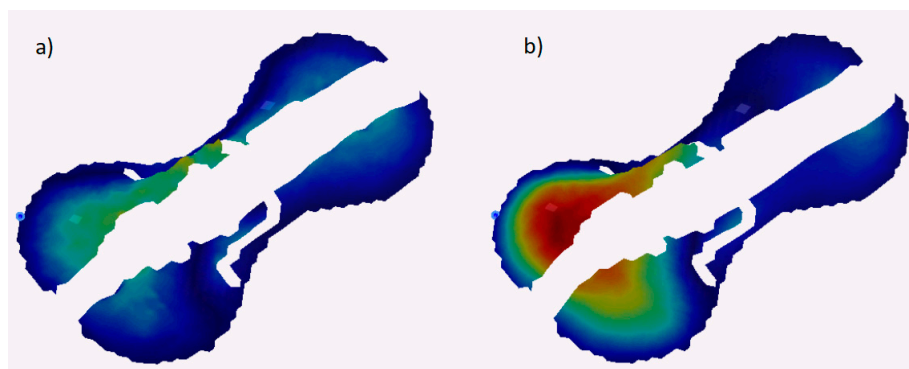
If we wish to have an entirely contactless measurement, we can excite the instrument with a speaker. Different signals were examined: burst chirp, periodic chirp, burst random, pseudo random, sweep and white noise. Of these signals a sweep allowed for the best coherence in a short measurement time (0.8 s per measurement). Although this should be sufficient to find the frequencies on which the modes occur, the exact placement of the speaker to the instrument has a large influence on the amplitude measured by the LDV, as shown in Figure 7.



**Figure 7.** Vibrational response in dB of different speaker placements for speaker excitation.

#### 4.1.2. Excitation through Shaker

By attaching a shaker to a part of the instrument, the measurement is not contactless anymore. However, the shaker can be mounted through a stinger on the bridge of the instrument, which allows for an excitation with a higher ecological validity. Through the shaker, the excitation signal can also be controlled better than through a not-automated modal hammer. CTA was examined again through this method. The A0 breathing mode was now found 8 Hz lower at 243 Hz and B1- at 3 Hz lower at 406 Hz (409 Hz). It must be noted however that the gluing of the stinger to the bridge will limit its ability to move freely. Figure 8 displays the measured A0 breathing and the B1- mode shape.



**Figure 8.** (a) A0 breathing mode at 243 Hz, (b) B1- mode at 406 Hz.

## 5. Conclusions

In our test, material properties seem to have a distinct influence on the amplitude of the vibrations of the instrument up to 2200 Hz. A0 and B1- mode could be identified and were found to be lower than in a conventional wooden violin. Although this must be verified by further testing, large differences in amplitudes between different instruments in specific frequency bands could play a role in the tonal color produced by the instrument.

**Author Contributions:** Due to the multidisciplinary field of this research, multiple researchers were needed in various stages of the research. T.D., M.K., E.S., M.L., G.V. and W.V.P. cooperated in the design of the experiment and analyses of the data; T.D. made the prototype violins with G.V. as supervisor. T.D. and E.S. set up the experimental modal analysis; T.D. performed the measurements; T.D. wrote the paper.

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