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Modal Parameters of Two Violins with Different Varnish Layers and Subjective Evaluation of Their Sound Quality

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Two violins were investigated. The only intentionally introduced difference between them was the type of varnish. One of the instruments was covered with a spirit varnish, the other was oil varnished. Experimental modal analysis was done for unvarnished/varnished violins and a questionnaire inquiry on the instrument's sound quality was performed. The aim of both examinations was to find differences and similarities between the two instruments in the objective (modal parameters) and subjective domain (subjective evaluation of sound quality). In the modal analysis, three strongly radiating signature modes were taken into account. Varnishing did not change the sequence of mode shapes. Modal frequencies A0 and B(1+) were not changed by oil varnishing compared to the unvarnished condition. For the oil varnished instrument, the frequency of mode B(1+) was lower than that of the same mode of the spirit varnished instrument. Our two violins were not excellent instruments, but before varnishing they were practically identical. However, after varnishing it appeared that the oil-varnished violin was better than the spirit-varnished instrument. Therefore, it can be assumed with a fairly high probability that also in general, the oil-varnished violins sound somewhat better than initially identical spirit-varnished ones.

Keywords: violins, modal analysis, varnish, subjective sound quality evaluation.

1. Introduction

Wooden musical instruments are usually coated with a so-called 'varnish', in order to protect them from moisture and dust and to enhance their visual appearance. These varnishes consist of one or more layers of mixed organic and mineral materials prepared by a luthier by grinding, mixing, solubilising and/or heating the raw materials. The mixtures are subsequently applied with a brush or a piece of cloth on a surface of a violin (Echard *et al.*, 2008). Violin-makers distinguish three main varnish types: (a) solutions of resins in alcohol, the so-called spirit varnishes, drying quickly by evaporation of the solvent, (b) solutions of resins in volatile oils, i.e. essential oil varnishes, drying more slowly, (c) mixtures of resins with siccative oils, i.e. oil varnishes, drying slowly. Volatile oils mainly used are turpentine oil and spike oil. The siccative oils most often used for oil varnishes are linseed and walnut oils. Colophony, Strasburg and Venice turpentines, sandarac, copals, benzoin, elemi, and mastic are vegetal resins typically used in violin varnishes. Shellac is a resin exuded by an insect (Echard *et al.*, 2007).

The dynamic behaviour of violins may be investigated by experimental and computational methods. Among those former, the most popular are optical measurements and modal analysis. A detailed modal analysis of a violin was done by Marshall (1985) and many others (Bissinger, 1995, 2003, 2008; Bissinger, Keiffer, 2003; Skrodzka *et al.*, 2009). However, a few reports were published on the effect of structural modifications on vibrational behaviour of violins, among them by Weinreich *et al.* (2000), examining a violin with holes drilled in the ribs, and the report by Meinel (1937), who measured the response curves for violins with and without varnish, with thick, normal, and thin plates. Thus, there are many papers about modal analysis of violins and one, rather historical (Meinel, 1937), on the influence of varnishing on violin's modal behaviour.

Basic information about the nature of vibration of a complete violin and its parts and behaviour of particular elements when strings are excited by different playing techniques can be found in handbooks by Cremer (1981); Fletcher and Rossing (1998), and Hartmann (1997).

Modal analysis technique has been extensively used to investigate a behaviour of particular elements of cellos, violins, and guitars, like a cello tailpiece (Fouilhe *et al.*, 2011), the violin bridge, and a soundpost (Bissinger, 1995; 2006; Saldner *et al.*, 2006), symmetric and asymmetric bracing patterns on guitar soundboards (Skrodzka *et al.*, 2011), isolated guitar soundboards (Elejabarrieta *et al.*, 2000; Boullosa, 2002), a complete Hutchins-Schelleng violin octet (Bissinger, 2003), complete violins (Marshall, 1985; Dünnwald, 1999), and many others.

The aim of the present work was to show differences (if any) in natural vibrations between two complete violins with intentionally introduced differences in varnishes. Parameters of natural vibrations (modal frequencies, modal damping, and modal deformations associated with them), being inherent properties of the structure, are responsible for the sound radiation from any vibrating mechanical system. Additionally, a subjective evaluation of the sound quality of violins was done by a simple auditory test.

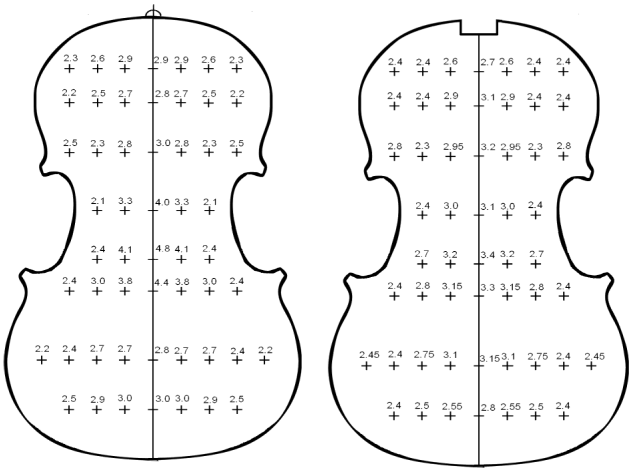


Fig. 1. Thickness of the front (right) and back (left) plates in mm.

Table 1. Violin sizes (mm).

	Front plate	Back plate
Body length	353	353
Maximum width in the upper bout	167.5	167.5
Width at the waist (arch)	110.5 (113.5)	110.5 (114.5)
Maximum width in the lower bout	206	206
Mensur length	–	195
Maximum height of arch	14	15.5
Ribs height	29–32	
Bass beam length	270	
Maximum bass beam height	13	
Bass beam width	3–6	
Bass beam position according to the instrument axis of symmetry	18 (upper part) 20 (bottom part)	

2. Experiment

2.1. Violins

Two replicas of the "Ysaÿe" violin of Giuseppe Guarneri del Gesu (1740) were made by a professional luthier. We named them "1" and "2". Top plates of both instruments were made of the same piece of spruce. Back plates, ribs, and heads were made of maple (sycamore). Special attention was paid to make both violins as similar as possible, if not identical. The only intentionally introduced difference was the coating varnish. Figure 1 shows the thickness of the front (right) and back (left) plates in millimetres. Violin sizes are listed in Table 1.

Both instruments were equipped with identical sets of strings: G – Pirastro Flexocore, D – Thomastik Infeld Red, A – Pirastro Chromcore Eudoxa, E – Pirastro Gold.

The first modal experiment was performed for both unvarnished instruments. The second modal experiment was done after varnishing. Before varnishing both violins were painted using wood stain of golden-brown colour tone. Next, the instruments were prime painted using linseed oil. Subsequently, instrument 1 was varnished using the spirit varnish; for instrument 2 the oil varnish was applied. The spirit varnish prepared by our luthier consisted of transparent spirit, ruby shellac, sandarac, mastic, gummi elemi, and benzoin. The oil varnish was JOHA® Oil Varnish, IA. This varnish contains a mixture of natural and synthetic resins, dissolved in turpentine and linseed oil, as well as essential oils such as lavender or rosemary. Golden yellow, golden brown, and amber colour extracts were used to obtain the desired colour shade. No siccatives were used. A badger painting brush was used. Violin 1 was covered with 20 layers of the spirit varnish and violin 2 with 10 layers of the oil varnish, following the common rules of varnishing, well known among violin makers. Both violins were measured in playing conditions with undamped strings at tension, without chin, or shoulder rest, similarly to Bissinger (2008).

2.2. Measurements

2.2.1. Modal analysis experiment

Modal analysis is a popular experimental method of studying dynamic behaviour of structures, including violins and guitars (Marshall, 1985; Ewins, 1995; Skrodzka *et al.*, 2005, 2006, 2011). The main assumption of the modal analysis is that the system under investigation is linear. In terms of the modal analysis, linearity means that interchanging the positions of the accelerometer and the impact hammer does not change the course of Frequency Response Functions (FRFs) obtained at these two positions. Thus, if the FRFs are the same, the Maxwell's reciprocity principle is valid and the system is linear. In reality, no mechanical system is linear but the assumption is not very strict (Marshall, 1985; Skrodzka *et al.*, 2011).

In terms of the modal analysis, the FRF for the response X_i at the point i, due to an excitation force F_k applied at the point k, has the form (Ewins, 1995; Marshall, 1985; Skrodzka, Sęk, 1998):

$$\frac{X_i}{F_k} = H_{ik}(s) = \sum_{r=1}^{n} \left(\frac{r_{ikr}}{s - p_r} + \frac{r_{ikr}^*}{s - p_r^*} \right), \tag{1}$$

where r_{ikr} is a residue for r-th mode, s is Laplace variable, $p_r = \sigma_r + j\omega_r$, for $k = 1, \ldots, r$ is the eigenvalue or the pole of the FRF, σ_r is the modal damping of the r-th mode, ω_r is the modal frequency of the r-th mode.

If all points i and k are taken into consideration, then Eq. (1) takes the form:

$$H(\omega) = \sum_{r=1}^{n} \left(\frac{\{u_r\}\{u_r\}^t}{j\omega - p_r} + \frac{\{u_r^*\}\{u_r^*\}^t}{j\omega - p_r^*} \right). \tag{2}$$

The Laplace variable s in Eq. (1) has been replaced by the frequency ω along the frequency axis; r_{ikr} and $\{u_r\}$ are complex quantities. Thus, each mode of vibration is defined by a pair of complex conjugate poles (p_r, p_r^*) and a pair of complex conjugate mode shapes ($\{u_r\}$, $\{u_r^*\}$); $\{u_r\}^t$ and $\{u_r^*\}^t$ are transpositions of $\{u_r\}$ and $\{u_r^*\}$, respectively. A set of FRFs with indices i and k is usually arranged in a matrix called a modal matrix.

The modal analysis method describes the dynamics of any vibrating system in terms of modal parameters: natural frequencies and natural damping, as well as deformation patterns (mode shapes) associated with them. As the measurement setup was similar to that described in our previous works (Skrodzka *et al.*, 2005, 2009, 2011), only the most crucial details are given below. For measurements, the instruments were mounted in a wooden cage of a significant mass, allowing the soundboard and the back plate to vibrate without any obstacles. The instruments were excited by an impact hammer to provide a broad-band excitation (PCB Impact Hammer 086C05, sensitivity 2.25 mV/N). As the version of the modal analysis with a fixed response point was used, the response signal was measured at the fixed measuring point marked as a black dot in Fig. 2. An ONO SOKKI NP-2910 accelerometer, with the mass of 2 g and sensitivity 0.3 pC/m/s^2 was used. The mass of the accelerometer was significantly less than 10% of the mass of the top of each instrument (about 120 g) and did not affect the results of the measurements. Both the excitation and the response signals were measured perpendicularly to the top plates, i.e. in the most important direction as regards the vibration of the final instrument. The accelerometer was mounted on a beewax. On the basis of these signals, the frequency response functions (FRFs) were calculated between all 230 excitation points on the front plate, see Fig.2, and the fixed response point where the accelerometer was mounted. The modal parameters extracted from the FRFs were calculated by means of an SMS STAR-Modal® package (The STAR system, 1990). The FRFs were measured at 230 points on the front plate. Geometry of the measuring mesh is shown in Fig. 2. A black dot in Fig. 2 denotes the position of the accelerometer. The position was chosen experimentally, avoiding areas of the top plate, where the bass bar was attached, and after a preliminary test, when the FRFs measured between some tested accelerometer positions and some points of excitation were evaluated by the experimenter with respect to a proper course of the coherence function and repeatable frequencies of peaks in FRFs.

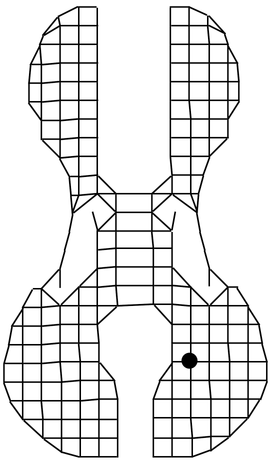


Fig. 2. Geometry of the modal analysis measuring mesh. The black dot denotes the position of the accelerometer.

All FRFs were measured in the frequency range 0–3200 Hz with a 4 Hz spectral resolution, and their quality was controlled by the coherence function. Ten spectral averages were used to improve the signal-to-noise ratio and FRFs.

2.2.2. *Performance subjective remarks*

To judge the sound quality of the varnished instruments, it was decided to evaluate them in natural playing conditions. Thirteen people with some experience in comparison of violin's sound (luthiery students) took part in the experiment. Their task was to fill up a questionnaire shown in Table 2 by assigning the mark "+" to the subjectively better instrument and mark "−" for the worse instrument. In the case when both instruments were evaluated equally they gave "+" (both good) or "−" (both bad). The questionnaire was similar to those used during luthier competitions. Subjects listened to sounds of violins in the concert hall of I.J. Paderewski Academy of Music. Subjects were informed about the symbol of presented instruments (1 or 2) and they were not informed about varnishing. Instructions concerning the questionnaire were given before the test. A professional violinist was the player. Subjects evaluated the sound of individual strings listening to the sounds: g (196 Hz), h (245 Hz), d^1 (294 Hz), f^1 (349 Hz), a^1 (440 Hz) on string G; d^1 (294 Hz), $f^{\#1}$ (370 Hz), c^2 (523 Hz), e^2 (659 Hz) on string D; a^1 (440 Hz), $c^{\#2}$ (554 Hz), e^2 (659 Hz), g^2 (784 Hz), h^2 (988 Hz) on string A; e^2 (659 Hz), $g^{\#2}$ (831 Hz), h^2 (988 Hz), d^3 (1175 Hz), $f^{\#3}$ (1480 Hz) on string E. Then scales were played on all strings and the task of the subjects was to evaluate the level and volume of the sound of all the strings. Finally, the Largo, C-major Sonata, BWV 1005 by J.S. Bach was played and the task of the subjects was to point out the instrument which according to them was better, with a more noble and interesting sound, or, in other words, they were asked about their general opinion about the level, range, and timbre of the sound.

Table 2. Questionnaire for the subjective evaluation of the sound quality.

	Sound	Violin 1	Violin 2
Sound of individual strings	Scale on string G		
	Scale on string D		
	Scale on string A		
	Scale on string E		
Level and equal volume of the sound of all the strings	Scale on all the strings	Level	Level
		Equal sound volume of strings	Equal sound volume of strings
General opinion about the level, range and timbre of the sound	J.S. Bach, Largo, C-major Sonata, BWV 1005		
General remarks			

3. Results

3.1. *Modal analysis*

A dozen or so modes were found in the frequency range measured. The mode shape sequence was similar to that well described in earlier papers and analyzed in a descriptive manner, being a widely accepted standard in the literature (Marshall, 1985; Dünnwald, 1999; Bissinger, 1995; 2003; 2008; Bissinger, Keiffer, 2003; Schleske, 2002; Skrodzka *et al.*, 2005; 2009, 2011). Our discussion of individual modes will be limited to three strongly radiating modes A0, B(1−) and B(1+) (Bissinger, 2008) of the top plate. These modes fall into the first Dünnwald frequency band (190–650 Hz) and are responsible for the sound "richness" (Dünnwald, 1999). A0 is a Helmholtz resonance ("air mode"). B(1−) and B(1+) are "plate modes" which arise from the bending and stretching of the front plate. For the top plate, the mode shape B(1−) has two longitudinal nodal curves placed almost symmetrically on both sides of the main axis of symmetry. Mode B(1+) on the top plate has two nodal curves crossing the upper and the lower bouts. In Table 3 the mode shapes, modal frequencies (f), and percentage of the critical damping (d) are shown for the above modes. Mode B(1−) of the oil varnished violin 2 presented in Table 3 was excluded from the analysis because of a high value of the critical damping ($> 10\%$). The main assumption of the modal analysis is linearity of the system under investigation. Strictly speaking, none of the violins is a linear system but it can be treated as such when critical damping is smaller than 10% (Skrodzka *et al.*, 2009; Ewins, 1995).

3.2. *Performance subjective remarks*

The results of the subjective evaluation of the sound quality of both varnished instruments are shown in Table 4. The evaluation of the individual strings was as follows: string G – nine persons pointed at violin 2, two persons – violin 1, and two subjects stated that in both instruments it sounded well. String D – eleven subjects preferred instrument 2, one subject – instrument 1, and for one person the string was good for both violins. String A – seven persons pointed at instrument 1, six – instrument 2. String E – eleven subjects preferred instrument 2, one subject – instrument 1, and for one subject the string was good in both instruments. When the sound level was evaluated, none of the instruments was significantly better: six subjects pointed at violin 2 and five persons preferred instrument 1; for one person both instruments were good, and for one both were bad. The strength of the sound was evaluated as better for violin 2 (twelve subjects); only one subject pointed out instrument 1. Instrument 2 covered with the oil varnish was

Table 3. Modal parameters for the top plate modes A0, B(1−) and B(1+). Mode B(1−) for the oil varnished instrument had a damping value exceeding 10% of the critical damping.

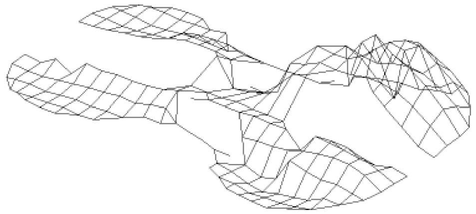
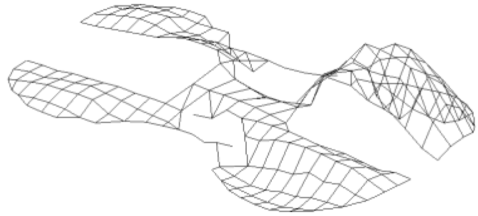
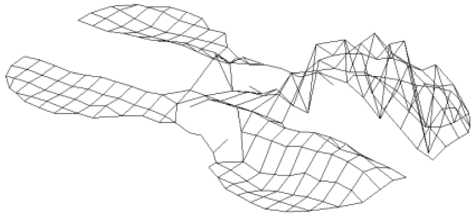
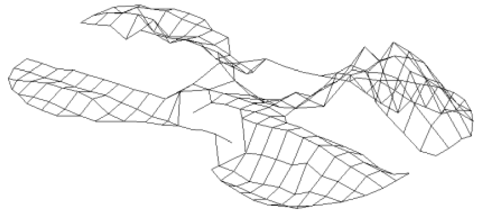
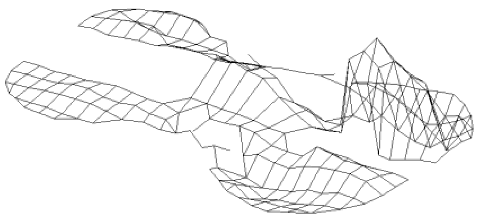
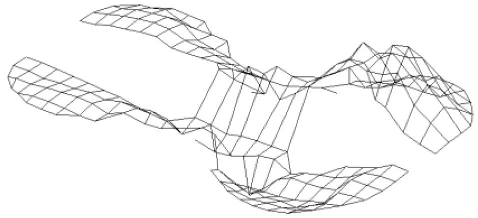
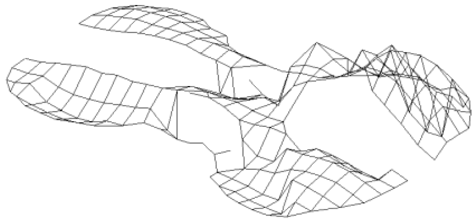
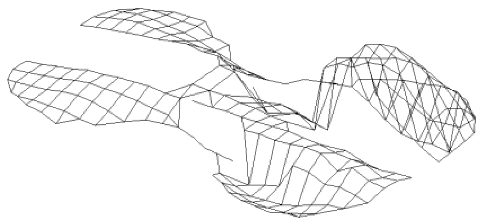
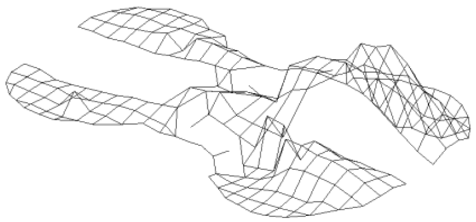
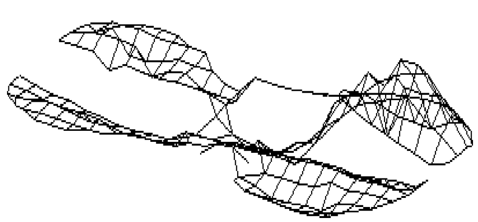
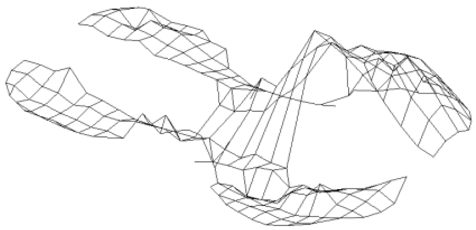
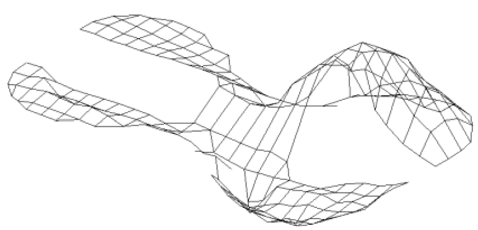
Mode	Violin 1 (white)	Violin 2 (white)
A0	 $f = 281$ Hz, $d = 10.0\%$	 $f = 280$ Hz, $d = 9.0\%$
B(1−)	 $f = 476$ Hz, $d = 9.6\%$	 $f = 451$ Hz, $d = 7.1\%$
B(1+)	 $f = 548$ Hz, $d = 8.1\%$	 $f = 540$ Hz, $d = 5.0\%$
	Violin 1 (spirit)	Violin 2 (oil)
A0	 $f = 277$ Hz, $d = 5.2\%$	 $f = 276$ Hz, $d = 6.4\%$
B(1−)	 $f = 492$ Hz, $d = 4.6\%$	 $f = 419$ Hz, $d = 17.0\%$
B(1+)	 $f = 598$ Hz, $d = 4.1\%$	 $f = 534$ Hz, $d = 5.1\%$

Table 4. Results of the subjective evaluation of the sound quality.

	Violin 1 (spirit) (+)	Violin 1 (spirit) (−)	Violin 2 (oil) (+)	Violin 2 (oil) (−)	Both good (+)	Both bad (−)
String G	9	2	2	9	2	0
String D	1	11	11	1	1	0
String A	7	6	6	7	0	0
String E	1	11	11	1	1	0
Sound level	5	6	6	5	1	1
Sound strength	1	12	12	1	0	0
Total	2	10	10	2	1	0

evaluated in total as better (10 persons) than the violin covered with the spirit varnish (2 subjects). For one subject the overall evaluation of both instruments was good.

4. Discussion

For unvarnished ("white") and varnished instruments, the mode shapes, modal frequencies, and modal damping of the modes under consideration were similar to those described in earlier papers (Marshall, 1985; Bissinger, 2003; 2008; Schleske, 2002). While comparing the modal frequencies of the unvarnished violins the only significant difference was found for mode B(1−), Table 3. Thus, modal parameters of the "white" instruments were very similar. Varnishing did not change the mode shapes but it influenced the modal frequencies, especially of modes B(1−) and B(1+). There was no systematic trend in the modal frequency changes. The modal frequency A0 was the same for both instruments before and after varnishing (measurement accuracy was 4 Hz). For mode B(1−) the modal frequency of "white" instrument 1 was 476 Hz and for the same instrument with the spirit varnish it was 492 Hz. A significant increase in the modal frequency for violin 1 was also observed for mode B(1+): from 548 Hz for the "white" instrument to 598 Hz for the varnished corpus. For unvarnished instrument 2, the frequency of mode B(1−) was 451 Hz; for the same violin with the oil varnish this mode was not observed with the assumed "damping limit" (10% of the critical damping). The modal frequency of mode B(1+) before varnishing was 540 Hz and 534 Hz after it. Thus, it was not changed by oil varnishing of violin 2 within the measurement accuracy of 4 Hz. By comparing the modal frequencies of the varnished instruments it was found that the modal frequency B(1+) was significantly lower for instrument 2 with the oil varnish (534 Hz) than for violin 1 with the spirit varnish (598 Hz). The modal damping was slightly reduced for both varnished corpuses when compared to the unvarnished instruments (Table 3), but this fact did not influence the violin's quality, as damping trends are not robust quality discriminators (Bissinger, 2008).

The frequency of mode B(1+) is very important for the violin sound and may be a "mechanical' gauge of the sound quality. According to Schleske it acts as a "tonal barometer" of the violin sound quality. When the frequency of mode B(1+) is lower than 510 Hz, an instrument is "soft", with a rather weak 'resistance' to the player, and its sound is dark. The instrument with B(1+) frequency higher than 550 Hz is 'stubborn', 'resistant' to the player, with a bright sound with a tendency of harshness (Bissinger, 2008; Schleske, 2002). The sound of our both varnished instruments was evaluated subjectively and the subjects pointed at the oil varnished violin to be better "in total" than the spirit varnished violin. This subjective feeling was objectively confirmed by the frequency of mode B(1+): for the oil varnished violin it was 543 Hz (less than 550 Hz) and for the spirit varnished violin it was much higher (598 Hz). Thus, by comparing the sound quality of the two varnished violins, oil varnished instrument, as evaluated subjectively and in agreement with comparative judgments of other authors (Bissinger, 2008; Fritz *et al.*, 2007; Schleske, 2002), was found better. It is worthwhile to note that famous 18th and 19th century instruments were usually oil varnished.

However, there are some reasons that keep us far away from a conclusion that the oil varnish has advantages over the spirit varnish when the sound quality of the violin is concerned. First, only two instruments were investigated. This number is obviously not appropriate for any statistical considerations. Nonetheless, similar situations, when only a few instruments were investigated with the aim of formulating general conclusions, can be found in some reports (Marshall, 1985; Skrodzka *et al.*, 2009; Weinreich *et al.*, 2000). Next, the "better" violin 2 probably is not acoustically 'excellent' because it did not outperformed violin 1 in all categories in the subjective test, and in the objective modal experiment the strongly radiating mode B(1−) was missing. Therefore, a better score obtained by violin 2 can be explained by the lower frequency of the "tonal barometer" B(1+). Finally, our investigations were carried out just after hardening of the varnish. Its drying and ageing induce important changes in its composition and may influence both the visual appearance and sound quality of the instrument.

5. Conclusions

An experimental modal analysis of two unvarnished and varnished violins, as well as a subjective evaluation of the sound quality of the varnished instruments, was done to find differences and similarities in the modal parameters and subjective judgment. Hence, we conclude that:

1. Our violins were not 'excellent' instruments, but before varnishing they were practically identical. However, after varnishing the subjects pointed out the oil-varnished violin as better than the spirit-varnished one. Therefore, it can be assumed with a fairly high probability that also in general, the oil-varnished violins sound somewhat better than initially identical spirit-varnished ones.
2. In the case of unvarnished violins the only difference in the modal frequency was observed for mode B(1−).
3. Varnishing did not change the mode shape sequence.
4. For the oil-varnished violin mode B(1−) was not taken into account due to a high value of the critical damping. The modal frequencies A0 and B(1+) were not changed by oil varnishing within a 4 Hz frequency measurement accuracy.
5. The frequency of a "tonal barometer" (mode B(1+)) was lower for the oil varnished instrument than the frequency of the same mode of the spirit varnished instrument. Thus, the objective value of this frequency suggested that the violin 2's sound quality was better.

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